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INTERNATIONAL STANDARD

colour inside

Rotating electrical machines –
Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

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IEC 60034-2-1:2024-03 RLV(en)

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ROTATING ELECTRICAL MACHINES –

Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC 60034-2-1:2014. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

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IEC 60034-2-1 has been prepared by IEC technical committee 2: Rotating machinery. It is an International Standard.

This third edition cancels and replaces the second edition of IEC 60034-2-1 published in 2014. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

Harmonization of layout and requirements with IEC 60034-2-2 and IEC 60034-2-3.

The text of this International Standard is based on the following documents:

Draft	Report on voting
2/2165/FDIS	2/2177/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 60034 series, published under the general title *Rotating electrical machines*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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ROTATING ELECTRICAL MACHINES –

Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

1 Scope

This part of IEC 60034 is intended to establish methods of determining efficiencies from tests, and also to specify methods of obtaining specific losses.

This document applies to DC machines and to AC synchronous and induction machines of all sizes within the scope of IEC 60034-1 rated for mains operation.

NOTE These methods may be applied to other types of machines such as rotary converters, AC commutator motors and single-phase induction motors.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60027-1, *Letter symbols to be used in electrical technology – Part 1: General*

IEC 60034-1:~~2010~~2022, *Rotating electrical machines – Part 1: Rating and performance*

~~IEC 60034-4:2008, *Rotating electrical machines – Part 4: Methods for determining synchronous machine quantities from tests*~~

IEC 60034-4-1:2018, *Rotating electrical machines – Part 4-1: Methods for determining electrically excited synchronous machine quantities from tests*

IEC 60034-19, *Rotating electrical machines – Part 19:Specific test methods for DC machines on conventional and rectifier-fed supplies*

IEC 60034-29, *Rotating electrical machines – Part 29: Equivalent loading and superposition techniques – Indirect testing to determine temperature rise*

IEC 60034-30-1, *Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code)*

IEC 60051(all parts), *Direct acting indicating analogue electrical measuring instruments and their accessories*

IEC 60051-1, *Direct acting indicating analogue electrical measuring instruments and their accessories – Part 1: Definitions and general requirements common to all parts*

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3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60034-1, IEC 60051-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
efficiency
ratio of output power to input power expressed in the same units and usually given as a percentage

3.2
direct efficiency determination
method by which the determination of efficiency is made by measuring directly the input power and the output power

~~**3.3**~~
~~**dynamometer**~~
~~device for measuring torque applied to the rotating part of the machine under test. It is equipped with means for measuring and indicating torque and speed, and is not limited to a cradle base construction. An in-line torque transducer may be used to provide a direct measurement of torque at the shaft of the machine under test.~~

~~**3.4**~~
~~**dynamometer test**~~
~~test in which the mechanical power output of a machine acting as a motor is determined by a dynamometer. Also a test in which the mechanical input power of a machine acting as a generator is determined by a dynamometer.~~

3.3
dual-supply back-to-back test
test in which two identical machines are mechanically coupled together, and the total losses of both machines are calculated from the difference between the electrical input to one machine and the electrical output of the other machine

3.4
indirect efficiency determination
method by which the determination of efficiency is made by measuring the input power or the output power and determining the total losses. Those losses are added to the output power, thus giving the input power, or subtracted from the input power, thus giving the output power

3.5
single-supply back-to-back test
test in which two identical machines are mechanically coupled together and are both connected electrically to the same power system. The total losses of both machines are taken as the input power drawn from the system

3.6
no-load test
test in which a machine is run as a motor providing no useful mechanical output from the shaft, or ~~when~~ if run as a generator with its terminals open-circuited

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3.7
zero power factor test ~~(synchronous machines)~~
no-load test on a synchronous machine, which is over-excited and operates at a power factor very close to zero

3.8
equivalent circuit method ~~(induction machines)~~
test on an induction machine in which the losses are determined by help of an equivalent circuit model

3.9
test with rotor removed and reverse rotation test ~~(induction machines)~~
combined test on an induction machine in which the additional load losses are determined from a test with rotor removed and a test with the rotor running in reverse direction to the rotating magnetic field of the stator

3.10
short-circuit test ~~(synchronous machines)~~
test on a synchronous machine in which a machine is run as a generator with its terminals short-circuited

3.11
locked rotor test
test in which the rotor is locked to prevent rotation

3.12
Eh-star test
test in which the motor is run in star connection on unbalanced voltage

3.13
losses

3.13.1
total losses
P_T
difference between the input power and the output power, equivalent to the sum of the constant losses (see 3.13.2), the load losses (see 3.13.4), the additional load losses (see 3.13.5) and the excitation circuit losses (see 3.13.3)

3.13.2
constant losses
P_c
losses incorporating the sum of windage, friction and iron losses

Note 1 to entry: Although these losses change with voltage and load, they are historically called "constant" losses and the name is retained in this document.

~~**3.13.2.1**~~
~~**constant losses**~~
~~P_c~~
~~sum of the iron losses and the friction and windage losses~~

3.13.2.1
iron losses
P_{fe}
losses in active iron and additional no-load losses in other ~~metal~~ magnetic and conductive parts

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3.13.2.2
friction and windage losses
P_{fw}
losses incorporating the sum of windage and friction

3.13.2.2.1
friction losses
losses due to friction (bearings and brushes, if not lifted at rated conditions) not including any losses in a separate lubricating system

3.13.2.2.2
windage losses
total losses due to aerodynamic friction in all parts of the machine, including power absorbed in shaft mounted fans, and in auxiliary machines forming an integral part of the machine

Note 1 to entry: Losses in a separate ventilating system should be listed separately.

Note 2 to entry: For machines indirectly or directly cooled by hydrogen, see IEC 60034-1.

3.13.3
excitation circuit losses

3.13.3.1
excitation circuit losses
P_e
sum of the excitation winding losses (see 3.13.3.2), the exciter losses (see 3.13.3.3) and, for synchronous machines, electrical brush loss (see 3.13.3.5), if any

3.13.3.2
excitation winding losses
P_f
excitation (field) winding losses are equal to the product of the exciting current I_e and the excitation voltage U_e

3.13.3.3
exciter losses
P_{Ed}
exciter losses for the different excitation systems (see Annex B) are defined as follows:

a) shaft driven exciter

exciter losses are the power absorbed by the exciter at its shaft (reduced by friction and windage losses) plus the power P_{1E} drawn from a separate source at its excitation winding terminals, minus the useful power which the exciter provides at its terminals. The useful power at the terminals of the exciter is equal to the excitation winding losses as per 3.13.3.2 plus (in the case of a synchronous machine) the electrical brush losses as per 3.13.3.5.

Note 1 to entry: If the exciter can be decoupled and tested separately its losses can be determined according to 7.1.3.2.1.5.

Note 2 to entry: Whenever the exciter makes use of separate auxiliary supplies, their consumptions are to be included in the exciter losses unless they are considered together with the main machine auxiliaries consumption.

b) brushless exciter

exciter losses are the power absorbed by the exciter at its shaft, reduced by friction and windage losses (when the relevant test is performed on the set of main machine and exciter), plus the electrical power P_{1E} from a separate source (if any) absorbed by its field winding or its stator winding (in the case of an induction exciter), minus the useful power which the exciter provides at the rotating power converter terminals.

Note 3 to entry: Whenever the exciter makes use of separate auxiliary supplies their consumptions are to be included in the exciter losses unless they are considered together with the main machine auxiliaries consumption.

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Note 4 to entry: If the exciter can be decoupled and tested separately, its losses can be determined according to 7.1.3.2.1.

c) separate rotating exciter

exciter losses are the difference between the power absorbed by the driving motor, plus the power absorbed by separate auxiliary supplies, of both driving and driven machines, including the power supplied by separate source to their excitation winding terminals, and the excitation power supplied as per 3.13.3.2 and 3.13.3.4. The exciter losses may be determined according to 7.1.3.2.1.

d) static excitation system

static exciter

excitation system losses are the difference between the electrical power drawn from its power source, plus the power absorbed by separate auxiliary supplies, and the excitation supplied as per 3.13.3.2 and 3.13.3.4.

Note 5 to entry: In the case of systems fed by transformers, the transformer losses shall be included in the exciter losses.

e) excitation from auxiliary winding

auxiliary winding exciter

exciter losses are the copper losses in the auxiliary (secondary) winding and the additional iron losses produced by increased flux harmonics. The additional iron losses are the difference between the losses which occur when the auxiliary winding is loaded and when it is unloaded.

Note 6 to entry: Because separation of the excitation component of losses is difficult, it is recommended to consider these losses as an integral part of the stator losses when determining overall losses.

In the cases c) and d) no allowance is made for the losses in the excitation source (if any) or in the connections between the source and the brushes (synchronous machine) or between the source and the excitation winding terminals (DC machine).

If the excitation is supplied by a system having components as described in b) to e) the exciter losses shall include the relevant losses of the components pertaining to the categories listed in Annex B as applicable.

3.13.3.4
separately supplied excitation power
$\boldsymbol{P_{1E}}$
excitation power P_{1E} supplied from a separate power source is:

– for exciter types a) and b) the exciter excitation power (DC or synchronous exciter) or stator winding input power (induction exciter). It covers a part of the exciter losses P_{Ed} (and further losses in induction exciters) while a larger part of P_e is supplied via the shaft;

– for exciter types c) and d) equal to the excitation circuit losses, $P_{1E} = P_e$;

– for exciter type e) $P_{1E} = 0$, the excitation power being delivered entirely by the shaft. Also, $P_{1E} = 0$ for machines with permanent magnet excitation.

Exciter types shall be in accordance with 3.13.3.3.

3.13.3.5
brush losses (excitation circuit)
$\boldsymbol{P_b}$
electrical brush loss (including contact loss) of separately excited synchronous machines

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3.13.4
load losses

3.13.4.1
load losses
P_L
sum of the winding (I^2R) losses (see 3.13.4.2) and the electrical brush losses (see 3.13.3.5), if any

3.13.4.2
winding losses
winding losses are I^2R losses:

– in the armature circuit of DC machines;
– in the stator and rotor windings of induction machines;
– in the armature and field windings of synchronous machines

3.13.4.3
brush losses (load circuits)
P_b
electrical brush loss (including contact loss) in the armature circuit of DC machines and in wound-rotor induction machines

3.13.5
additional load losses (stray-load losses)
P_{LL}
losses produced in active iron and other metal magnetic and conductive parts by alternating stray fluxes when the machine is loaded; eddy current losses in winding conductors caused by load current-dependent flux pulsations and additional brush losses caused by commutation

Note 1 to entry: These losses do not include the additional no-load losses of 3.13.2.2.

3.13.6
short-circuit losses
P_k P_{sc}
current-dependent losses in a synchronous machine and in a DC machine when the armature winding is short-circuited

3.14
test quantities <polyphase AC machines>

3.14.1
terminal voltage
for polyphase AC machines, the arithmetic average of line voltages

3.14.2
line current
for polyphase AC machines, the arithmetic average of line currents

3.14.3
line-to-line resistance
for polyphase AC machines, the arithmetic average of resistances measured between each pair of terminals

Note 1 to entry: For Y-connected three-phase machines, the phase-resistance is 0,5 times the line-to-line resistance. For Δ-connected machines, the phase-resistance is 1,5 times the line-to-line resistance.

Note 2 to entry: In Clauses 6 and 7 explanations and formulae given are for three-phase machines, unless otherwise indicated.

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3.14.4
temperature rise
is the machine temperature minus the cooling medium (coolant) temperature as defined by IEC 60034-1

4 Symbols and abbreviated terms

4.1 Symbols

cos φ	is the power factor[1]
f	is the supply frequency, Hz
I	is the ~~average~~ line current (average of all phases), A
k_{θ}	is the temperature correction factor
n	is the operating speed, s^{-1}
p	is the number of pole pairs
P	is the power, W
P_0	is the input power at no-load, W
P_1	is the input power, excluding excitation[2], W
P_2	is the output power, W
P_b	is the brush loss, W
P_D	is the output power (shaft power) of a drive motor, W
P_e	is the excitation circuit losses, W
P_{1E}	is the excitation power supplied by a separate source, W
P_{Ed}	is the exciter losses, W
P_{el}	is the electrical power, excluding excitation, W
P_f	is the excitation (field) winding losses, W
P_{fe}	is the iron losses, W
P_{fw}	is the friction and windage losses, W
P_c	is the constant losses, W
P_L	is the load losses, W
P_{Lr}	is the residual losses, W
P_{LL}	is the additional-load losses, W
~~P_k~~ P_{sc}	is the short-circuit losses, W
P_{mech}	is the mechanical power, W
P_T	is the total losses, W
P_w	is the winding losses, W, where subscript w is generally replaced by a, f, e, s or r (see 4.2)
R	is a winding resistance, Ω

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[1] This definition assumes sinusoidal voltage and current.

[2] Unless otherwise indicated, the tests in this document are described for motor operation, where P_1 and P_2 are electrical input and mechanical output power, respectively.

R_{eh}	is the actual value of the auxiliary resistor for the Eh-star test (see 6.2.5), Ω
R'_{eh}	is the typical value of the auxiliary resistor, Ω
R_f	is the field winding resistance, Ω
R_{ll}	is the ~~average~~ line-to-line-resistance (average of all phases), Ω
R_{ph}	is the ~~average~~ phase-resistance (average of all phases), Ω
s	is the slip, in per unit value of synchronous speed
T	is the machine torque, N·m
T_d	is the reading of the torque measuring device, N·m
~~T_c~~	~~is the torque correction, N·m~~
U	is the ~~average~~ terminal voltage (average of all phases), V
U_0	is the terminal voltage at no-load (average of all phases), V
U_N	is the rated terminal voltage, V
X	is the reactance, Ω
$\underline{Z} = R + j \times X$	is the notation for a complex quantity (impedance as example)
$Z = \lvert\underline{Z}\rvert = \sqrt{R^2 + X^2}$	is the absolute value of a complex quantity (impedance as example)
Z	is the impedance, Ω
α	is a temperature coefficient
η	is the efficiency
θ_0	is the initial winding temperature, °C
θ_a	is the ambient temperature, °C
θ_c	primary coolant inlet temperature, °C
θ_w	is the winding temperature, °C
τ	is a time constant, s

4.2 Additional subscripts

The following subscripts may be added to symbols to clarify the machine function and to differentiate values.

Machine components:

a	armature
e	excitation
f	field winding
r	rotor
s	stator
w	winding
U,V,W	phase designations

Machine categories:

B	booster
~~D~~	~~dynamometer~~

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E exciter
G generator
M motor

Operating conditions:

0 no-load
1 input
2 output
av average, mean
d dissipated
el electrical
i internal
~~k~~ sc short circuit
L test load
lr locked rotor
mech mechanical
N rated
red at reduced voltage
t test
zpf zero power factor test
θ corrected to a reference coolant temperature.

NOTE Further additional subscripts are introduced in relevant subclauses.

5 Basic requirements

5.1 Direct and indirect efficiency determination

Tests can be grouped into the three following categories:

a) input-output power measurement on a single machine. This involves the direct measurement of electrical or mechanical power into, and mechanical or electrical power out of a machine;
b) electrical input and output measurement on two identical machines mechanically connected back-to-back. This is done to eliminate the measurement of mechanical power into or out of the machine;
c) determination of the actual loss in a machine under a particular condition. This is usually not the total loss but comprises certain loss components.

The methods for determining the efficiency of machines are based on a number of assumptions. Therefore, it is not recommended that a comparison be made between the values of efficiency obtained by different methods, because the figures may not necessarily agree.

5.2 Uncertainty

Uncertainty as used in this standard is the uncertainty of determining a true efficiency. It reflects variations in the test procedure and the test equipment.

Although uncertainty ~~should~~ shall be expressed as a numerical value, such a requirement needs sufficient testing to determine representative and comparative values.

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5.3 Preferred methods and methods for customer-specific acceptance tests, field-tests or routine-tests

It is difficult to establish specific rules for the determination of efficiency. The choice of test to be made depends on the information required, the accuracy required, the type and size of the machine involved and the available field test equipment (supply, load or driving machine).

In the following, the test methods suitable for asynchronous and synchronous machines are separated into preferred methods and methods for customer-specific acceptance tests, field-tests or routine tests.

5.4 Power supply

5.4.1 Voltage

The supply voltage shall be in accordance with 7.2 (and 8.3.1 for thermal tests) of IEC 60034-1:~~2010~~2022.

5.4.2 Frequency

During tests, the average supply frequency shall be within ±0,1 % of the frequency required for the test being conducted.

5.5 Instrumentation

5.5.1 General

Environmental conditions shall be within the recommended range given by the ~~equipment~~ instrument manufacturer. If appropriate, temperature corrections according to the ~~equipment~~ instrument manufacturer's specification shall be made.

Digital instruments shall be used whenever possible.

For analogue instruments accuracy is generally expressed as a percentage of full scale, the range of the instruments chosen shall be as small as practical.

The full scale of the ~~equipment~~ instrument, particularly the current sensors, shall be adapted to the power of the machine under test.

For analogue instruments the observed values should be in the upper third of the instrument range.

When testing electric machines under load, slow fluctuations in the output power and other measured quantities may be unavoidable. Therefore, for each load point many ~~samples~~ readings (typically many hundred ~~samples~~ readings) shall be taken automatically by a suitable digital meter over a period of several fluctuation cycles, at least 5 s but not more than ~~15~~ 60 s and this average shall be used for the determination of efficiency.

5.5.2 Measuring instruments for electrical quantities

The measuring instruments shall have the equivalent of an accuracy class of 0,2 in case of a direct test and 0,5 in case of an indirect test in accordance with IEC 60051. The measuring equipment shall reach a maximum overall uncertainty of 0,2 % of reading at power factor 1,0 and shall include all errors of instrument transformers or transducers, if used.

NOTE For a routine test as described in IEC 60034-1 an accuracy class of 0,5 is sufficient.

In the case of AC machines, unless otherwise stated in this standard, the arithmetic average of the line currents and voltages shall be used.

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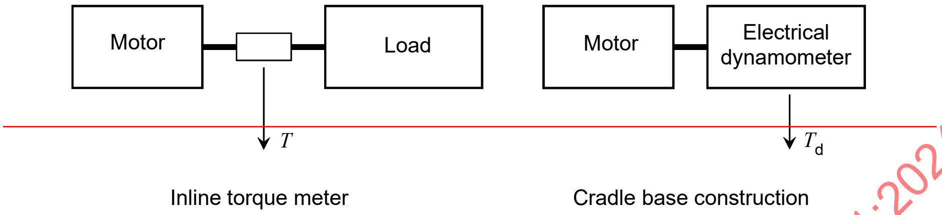
5.5.3 Torque measurement

~~The instrumentation used to measure~~ The torque measuring device shall have a minimum class of 0,2. The minimum torque measured shall be at least 10 % of the torque meter's nominal torque. This applies also to part load measurements, because of increased instrument uncertainty at small readings. If a better class instrument is used, the allowed torque range can be extended accordingly.

NOTE For example class 0,1 means 5 % of the torque meter's nominal torque.



~~When the shaft torque is measured by means of a dynamometer with a cradle base construction, a torque correction test shall be carried out to compensate the friction losses in the bearings of the loading machine. This also applies if any other bearing is interposed between the torque measuring device and the motor shaft.~~

~~The machine torque T is calculated using the formula:~~

$$T = T_d + T_c$$

~~Where~~

~~T_d is the torque reading of the load test;~~

~~T_c is the torque correction due to friction losses.~~

Allowed torque measuring device are an inline torque meter or a reaction torque sensor between the machine and its base. In the latter case the machine is directly coupled to the load. See Figure 2.

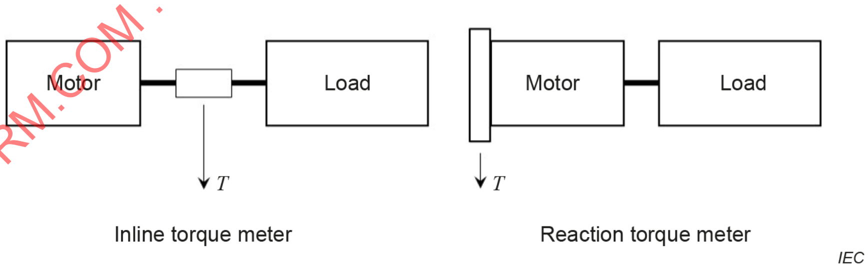


Figure 1 – Torque measuring devices

It ~~has to~~ shall be noted that the temperature of the torque sensor (i.e., ~~near~~ due to proximity to the rotor), may be higher than the ambient temperature and is acknowledged to have a significant contribution to overall uncertainty. In that case the contribution of temperature to the uncertainty shall be limited to 0,15 % of full scale. If that is not practical, an appropriate temperature correction ~~has to~~ shall be applied.

Parasitic loads should be minimized by shaft alignment and the use of flexible couplings.

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5.5.4 Speed and frequency measurement

The instrumentation used to measure supply frequency shall have an accuracy of ±0,1 % of full scale. The speed measurement should be accurate within 0,1 revolution per minute.

NOTE 1 Speed in min^{-1} is n in $s^{-1} \times 60$.

NOTE 2 For asynchronous machines, the measurement of slip by a suitable method may replace speed measurement (see Annex C).

5.5.5 Temperature measurement

The instrumentation used to measure temperatures shall have an accuracy of ±1 K.

5.6 Units

Unless otherwise specified, the units of values are SI-units as listed in IEC 60027-1.

5.7 Resistance

5.7.1 Test resistance

Winding resistance R is the ohmic value, determined by appropriate methods.

For DC machines, R is the total resistance of all windings carrying armature current (armature, commutating commutation, compensating winding, compound winding).

For DC and synchronous machines, R_f is the field winding resistance.

For polyphase AC machines, $R = R_{ll}$ is the line-to-line average resistance of the stator or armature winding according to 3.14.3. In the case of wound rotor induction machines, $R_{r,ll}$ is the rotor line-to-line average resistance.

The measured resistance at the end of the thermal test shall be determined in a similar way to the extrapolation procedure, as described in 8.6.2.3.3 of IEC 60034-1, using the shortest possible time instead of the time interval specified in Table 5 therein, and extrapolating to zero.

The measured resistance at the end of the thermal test shall be determined as soon as possible but not after more than twice the interval as specified in Table 6 of IEC60034-1:2022. Additional readings shall be taken at intervals of approximately 1 min until these readings have begun a distinct decline from their maximum value. A curve of these readings shall be plotted as a function of time and extrapolated to zero. The value of temperature thus obtained shall be considered as the temperature at shutdown.

The measured temperature of windings shall be determined according to 5.7.2.

5.7.2 Winding temperature

The measured winding temperature shall be determined by one of the following methods (shown in order of preference):

a) temperature determined from the rated load test resistance R_N by the extrapolation procedure as described in 5.7.1;

NOTE Motors that are subject to check testing for regulatory purposes are not to be dismantled. In that case, measurement of winding temperature shall be by the change of resistance method.

b) temperature measured directly by either ETD or thermocouple; if the temperature is measured by more than one ETD or thermocouple, the average of all readings shall be taken;

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c) temperature determined according to a) on a duplicate machine of the same construction and electrical design;

d) ~~when~~ if load capability is not available, determine operating temperature according to IEC 60034-29;

e) ~~when~~ if the rated load test resistance R_N cannot be measured directly, the winding temperature shall be assumed to be equal to the reference temperature of the rated thermal class as given in Table 1.

Table 1 – Reference temperature

Thermal class of the insulation system	Reference temperature °C
130 (B)	95
155 (F)	115
180 (H)	135

If the rated temperature rise or the rated temperature is specified as that of a lower thermal class than that used in the construction, the reference temperature shall be that of the lower thermal class.

Motors that are subject to check testing for regulatory purposes are not to be dismantled. In that case, measurement of winding temperature shall be by the change of resistance method;

5.7.3 Correction to reference coolant temperature

~~When~~ If required, the winding resistance values recorded during test shall be referred to a standard reference temperature of 25 °C. The correction factor to adjust the winding resistance (and the slip in the case of cage induction machines) to a standard reference coolant temperature of 25 °C shall be determined by

$$k_\theta = \frac{235 + \theta_w + 25 - \theta_c}{235 + \theta_w} \qquad (1)$$

where

k_θ is the temperature correction factor for windings;

θ_c is the ~~inlet~~ primary coolant temperature during test;

θ_w is the winding temperature according to 5.7.2.

The temperature constant 235 is for copper; this should be replaced by 225 for aluminium conductors.

For machines with water as the primary or secondary coolant, the water reference temperature shall be 25 °C according to Table 5 of IEC 60034-1:~~2010~~2022. Alternative values may be specified by agreement.

5.8 State of the machine under test and test categories

Tests shall be conducted on an assembled machine with the essential components in place, to obtain test conditions equal or very similar to normal operating conditions.

For handling of sealing systems for efficiency classification related measurements see IEC 60034-30-1.

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~~NOTE 1~~ It is preferable that the machine be selected randomly from series production without special considerations.

~~Externally accessible sealing elements may be removed for the tests, if an additional test on machines of similar design has shown that friction is insignificant after adequately long operation.~~

~~NOTE 2 Motors with bearings and/or internal seals which are known to have less friction after adequately long operation, can be subjected to a run in before test.~~

The sub-tests that make up a test procedure shall be performed in the sequence listed. It is not essential that the tests be carried out immediately one after another. However, if the sub-tests are performed with delay, then the specified thermal conditions shall be re-established prior to obtaining the test data.

For machines with adjustable brushes, the brushes shall be placed in the position corresponding to the specified rating. For induction motors with wound rotor having a brush lifting device, the brushes shall be lifted during tests, with the rotor winding short-circuited. For measurements on no-load, the brushes shall be placed in the neutral axis on DC machines.

For machines having brushes, during the rated load test, and prior to any measurement, a visual inspection shall be done to check if the brushes are fully bedded, and a proper skin is developed.

The bearing losses depend on the operating temperatures of the bearings, the type of lubricant and lubricant temperature.

~~When~~ If the losses in a separate lubricating system of bearings are required these should be listed separately.

In the case of motors which are furnished with thrust bearings, only that portion of the thrust bearing loss produced by the motor itself shall be included in the total losses.

Friction losses due to thrust load may be included by agreement.

If the tested machine uses direct flow cooling of the bearings, these losses are distributed between the tested machine and any other one coupled to it mechanically, such as a turbine, in proportion to the masses of their rotating parts. If there is no direct flow cooling, the distribution of bearing losses shall be determined from empirical formulae by agreement.

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5.9 Excitation circuit measurements

Determination of voltage U_e and current I_e (see 3.13.3.2) depends on the configurations of the excitation system (see 3.13.3.3). Where applicable, test data shall be recorded according to the following:

a) for machines excited by shaft driven, separate rotating, static and auxiliary winding exciters (see 3.13.3.3 a), c), d) and e)), voltage U_e and current I_e are measured:
   – at the excitation winding terminals of DC machines;
   – at the field winding slip-rings of synchronous machines;

b) for machines excited by brushless exciters (see 3.13.3.3 b)), test data shall be recorded by either of the following methods:
   – voltage U_e measured using auxiliary (provisional) slip-rings connected to the field winding ends. From the voltage and resistance R_e determine the field winding current $I_e = \dfrac{U_e}{R_e} = \dfrac{U_f}{R_f}$. The field winding resistance is to be measured after switching off the machine using the extrapolation procedure according to 5.7.1;

– voltage U_e and current I_e measured using power slip-rings suitable for direct measurement of field winding current.

NOTE The difference between U_e and U_f (voltage drop of brushes) is in practice almost negligible.

Voltages and currents shall be measured at stabilized temperatures.

The excitation circuit losses P_e are determined according to 7.1.3.2.1.5 (synchronous machines) or 8.3.2.1.5 (DC machines).

5.10 Ambient temperature during testing

The ambient temperature should be in the range of 15 °C to 30 40 °C for at least the last hour of the rated load thermal test and all subsequent tests and measurements.

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6 Test methods for the determination of the efficiency of induction machines

6.1 Preferred testing methods

6.1.1 General

This document defines three different preferred methods with low uncertainty within the given range of application, see Table 2. The specific method to be used depends on the type or rating of the machine under test:

Method 2-1-1A: Direct measurement of input and output power by using a dynamometer torque measuring device. To be applied for all single phase machines.

Method 2-1-1B: Summation of separate losses. Additional load loss determined by the method of residual loss. To be applied for all three phase machines with rated output power up to 2 MW. See also Annex D.

Method 2-1-1C: Summation of separate losses. Additional load loss determined by the method of assigned value. To be applied for all three phase machines with rated output power greater than 2 MW.

Table 2 – Induction machines: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-1A	**Direct measurement:** **Input-output**	Torque measurement	6.1.2	All single phase machines	Dynamometer Torque measuring device for full-load
2-1-1B	**Summation of losses:** **Residual losses**	P_{LL} determined from residual loss	6.1.3	Three phase machines with rated output power up to 2 MW	Dynamometer Torque measuring device for 1,25 × full-load, or load machine for 1,25 × full-load with torque meter measuring device
2-1-1C	**Summation of losses:** **Assigned value**	P_{LL} from assigned value	6.1.4	Three phase machines with rated output power greater than 2 MW	

6.1.2 Method 2-1-1A – Direct measurement of input and output

6.1.2.1 General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the stator is measured in the same test.

Input and output power are:

in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 2); (2)

in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$ (3)

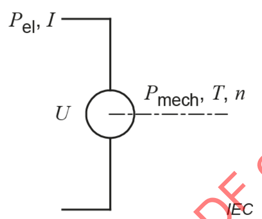

Figure 2 – Sketch for torque measurement test

For an overview, Figure 3 provides a flowchart for efficiency determination by this test method.

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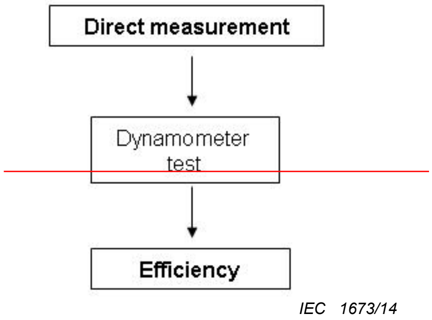

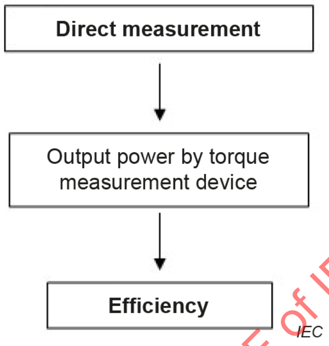

Figure 3 – Efficiency determination according to method 2-1-1A

6.1.2.2 Test procedure

Couple the machine under test to a load machine with torque ~~meter or a dynamometer~~ measuring device. Operate the machine under test at the required load until thermal equilibrium is achieved (rate of change 1 K or less per half hour).

Record U, I, P_{el}, n, T, θ_c.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

6.1.2.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1} \tag{4}$$

Input power P_1 and output power P_2 are:

in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$; (5)

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in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$ (6)

where

$$P_{mech} = 2\pi \times T \times n \quad (7)$$

6.1.3 Method 2-1-1B – Summation of losses, additional load losses according to the method of residual loss

6.1.3.1 General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

– iron loss;
– windage and friction losses;
– stator and rotor copper losses;
– additional load losses.

For an overview, Figure 4 provides a flowchart for efficiency determination by this test method.

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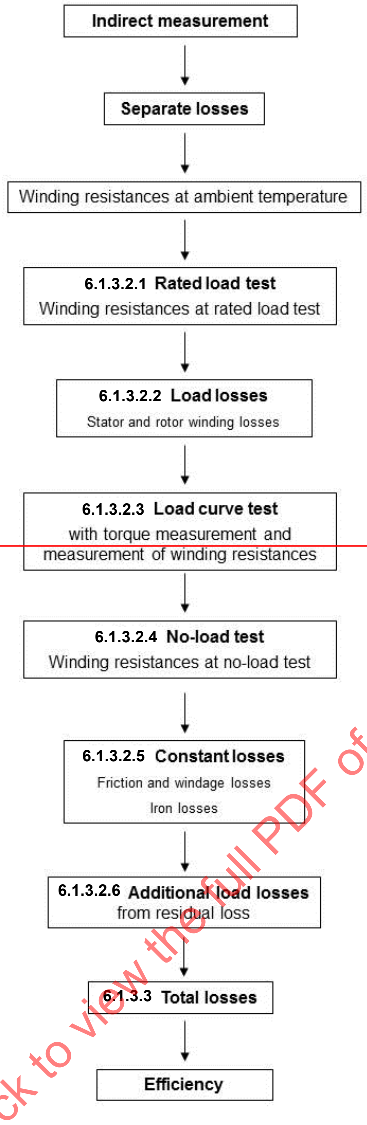

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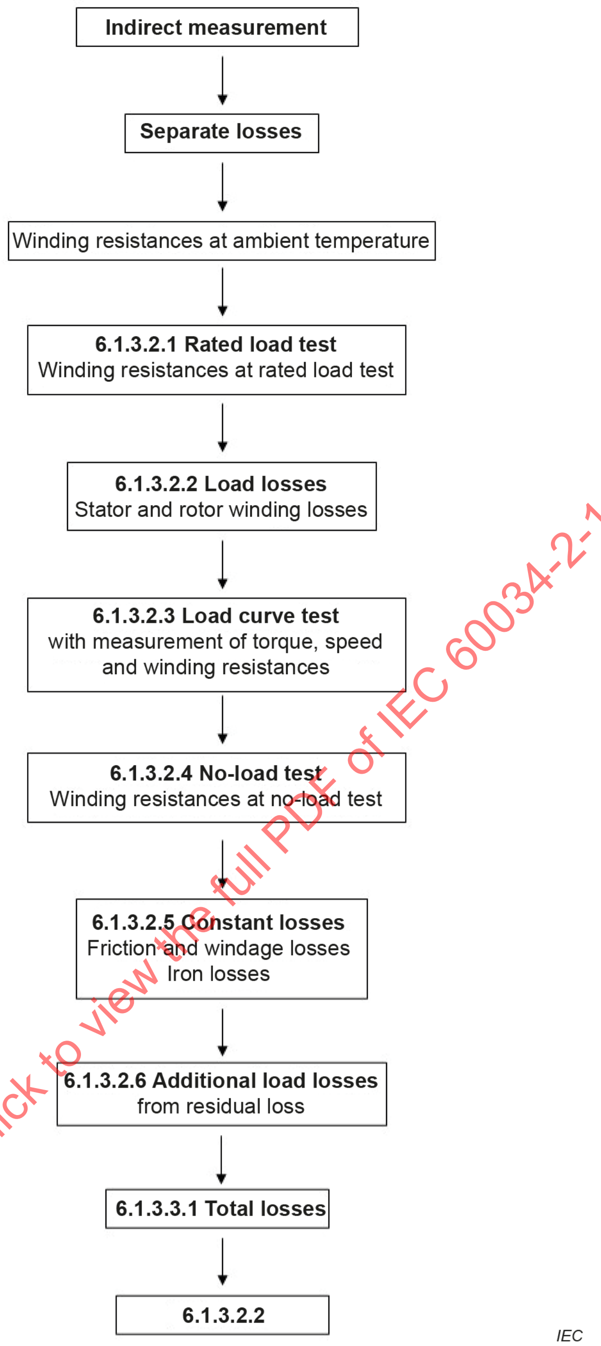

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Figure 4 – Efficiency determination according to method 2-1-1B

6.1.3.2 Test procedure

6.1.3.2.1 Rated load test

Before this load test, measure the temperature and the winding resistance of the motor with the motor at ambient temperature.

The machine shall be loaded by suitable means with rated output power and operated until thermal equilibrium is achieved (rate of change 1 K or less per half hour). Record the following quantities:

– P_1, T, I, U, n, f, θ_c, θ;

– $R_N = R$ (the test resistance for rated load according to 5.7.1);

– θ (the winding temperature at rated load according to 5.7.2).

Immediately after the load test, the drift of the torque transducer ~~should~~ shall be checked. In case of a deviation above the allowed tolerance of the transducer, adjust it and repeat the measurements.

6.1.3.2.2 Load losses

6.1.3.2.2.1 Stator-winding losses and temperature correction

The uncorrected stator-winding losses at rated load are:

$$P_s = 1{,}5 \times I^2 \times R \qquad (8)$$

where I and R are determined in 5.7.1.

Determine the stator-winding losses, using the stator winding resistance R_N from the rated load test, corrected to a reference coolant temperature of 25 °C:

$$P_{s,\theta} = P_s \times k_\theta \qquad (9)$$

where k_θ is the correction according to 5.7.3 for the stator winding.

6.1.3.2.2.2 Rotor winding losses and temperature correction

For the uncorrected rotor winding losses use the formula:

$$P_r = (P_1 - P_s - P_{fe}) \times s \qquad (10)$$

where

$$s = 1 - \frac{p \times n}{f} \qquad (11)$$

P_1, n and f are according to the rated load test;

P_s according to the load test as stated above;

P_{fe} is according to 6.1.3.2.5.

The corrected rotor winding losses are determined using the corrected value of the stator winding losses:

$$P_{r,\theta} = (P_1 - P_{s,\theta} - P_{fe}) \times s_\theta$$

where

P_{fe} is according to 6.1.3.2.5 for a reference coolant temperature of 25 °C;

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$s_\theta = s \times k_\theta$ is the slip corrected to a reference coolant temperature of 25 °C (see 5.7.3);

k_θ is the correction according to 5.7.3.

6.1.3.2.2.3 Temperature correction of input power (for a motor)

With the corrected stator and rotor winding losses, the corrected input power is:

$$P_{1,\theta} = P_1 - (P_s - P_{s,\theta} + P_r - P_{r,\theta}) \tag{12}$$

6.1.3.2.3 Load curve test

This test shall be carried out immediately after the rated load test with the motor at operating temperature.

If that is not possible, prior to the start of recording data for this test, the temperature rise of the windings shall be within 5 K of the initial temperature rise θ_N, obtained from a rated load temperature test.

Apply the load (shaft power) to the machine at the following six load points: approximately 125 %, 115 %, 100 %, 75 %, 50 % and 25 % of rated load. These tests shall be performed as quickly as possible to minimize temperature changes in the machine during testing.

NOTE 1 As an indication, the applied load may vary by ± 5 % from the figures given above. The impact on the further evaluation of the residual losses is limited.

Supply frequency variation between all points shall be less than 0,1 %.

Measure R before the highest and after the lowest load reading. The resistance for 100 % load and higher loads shall be the value determined before the highest load reading. The resistance used for loads less than 100 % shall then be determined as varying linearly with load, using the reading before the test for the highest load and after the lowest reading for 25 % load.

NOTE 2 Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each load point may then be determined from measured resistance before load curve test multiplied with the ratio of the temperature of the winding at that load point ~~in relation~~ to the ~~resistance and~~ temperature of the winding measured before the start of the test.

Record for each load point: U, I, P_1, n, f, T.

~~**Stator-winding losses**~~

The stator-winding losses at each of the load points are:

$$P_s = 1{,}5 \times I^2 \times R \tag{13}$$

where I and R are determined according to 6.1.3.2.2 for each load point.

~~**Rotor winding losses**~~

For the rotor winding losses for each of the load points use the formula:

$$P_r = (P_1 - P_s - P_{fe}) \times s \tag{14}$$

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where

$$s = 1 - \frac{p \times n}{f} \tag{15}$$

P_1, n and f	are according to the load curve test;
P_s	is according to the load curve test as stated above;
P_{fe}	is according to 6.1.3.2.5.

6.1.3.2.4 No-load test

The no-load test shall be carried out on a hot machine immediately after the load curve test.

Alternatively, the test may also be carried out with stabilized no-load losses. The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at the following eight values of voltage, including rated voltage, so that:

- the values at approximately 110 %, 100 %, 95 % and 90 % of rated voltage are used for the determination of iron losses;
- the values at approximately 60 %, 50 %, 40 % and 30 % of rated voltage are used for the determination of windage and friction losses.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linearly with the electrical power P_0.

~~NOTE 1~~ For induction machines R_0 is $R_{ll,0}$. Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

NOTE ~~2 In a.c. machines,~~ Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each voltage point may then be determined from measured resistance before no-load test multiplied with the ratio of the temperature of the winding at that load point ~~in relation~~ to the ~~resistance and~~ temperature of the winding measured before the start of the test.

For a coupled machine, P_0 is determined from T and n.

6.1.3.2.5 Constant losses

6.1.3.2.5.1 General

Subtracting the no-load winding losses from the no-load input power gives the constant losses that are the sum of the friction, windage and iron losses. Determine the constant losses for each value of voltage recorded.

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$$P_c = P_0 - P_s = P_{fw} + P_{fe} \tag{16}$$

where

$$P_s = 1{,}5 \times I_0^2 \times R_{ll,0} \tag{17}$$

with $R_{ll,0}$ being the interpolated winding resistance at each voltage point.

6.1.3.2.5.2 Friction and windage losses

From the four or more consecutive no-load loss points between approximately 60 % of voltage and 30 % of voltage develop a curve of constant losses (P_c) against the voltage squared (U_0^2).

Extrapolate a straight line to zero voltage. Determine the intercept at zero voltage, which is considered the friction and windage losses P_{fw0} at approximately synchronous speed.

6.1.3.2.5.3 Iron losses

From the values of voltage between approximately 90 % and 110 % of rated voltage, develop a curve of $P_{fe} = P_c - P_{fw}$ against voltage U_0.

To determine the iron losses at full load the inner voltage U_i that takes the resistive voltage drop in the primary winding into account shall be calculated:

$$U_i = \sqrt{\left(U - \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \sin\varphi\right)^2} \quad \text{for a motor} \tag{18}$$

$$U_i = \sqrt{\left(U + \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \sin\varphi\right)^2} \quad \text{for a generator} \tag{19}$$

Where

$$\cos\varphi = \frac{P_1}{\sqrt{3} \times U \times I}; \qquad \sin\varphi = \sqrt{1 - \cos^2\varphi} \tag{20}$$

U, P_1, I and R are from the load test according to 6.1.3.2.1.

The iron losses at full load shall be interpolated from the iron losses over voltage U_0 curve at the voltage U_i.

NOTE ~~1~~ The iron losses at full load may be calculated by using the ratio (~~Ur~~ U_i/U_N)^2 applied to the iron losses at no-load.

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~~NOTE 2~~ Because the stator leakage inductance is unknown, the voltage is only considering the resistive voltage drop. Due to the low power factor at no-load, the resistive voltage drop is negligible during the measurement itself and shall only be taken into consideration for the load values.

6.1.3.2.6 Additional load losses P_{LL}

6.1.3.2.6.1 Residual losses P_{Lr}

The residual losses shall be determined for each load point by subtracting from the input power: the mechanical output power, the uncorrected stator winding losses at the resistance of the test, the adjusted iron losses, the corrected windage and friction losses, and the uncorrected rotor winding losses corresponding to the determined value of slip.

The iron losses at each load point shall be interpolated from the iron losses over voltage U_0 curve at the voltage U_i for the respective load point.

$$P_{Lr} = P_1 - P_2 - P_s - P_r - P_{fe} - P_{fw}\,; \qquad (21)$$

$$P_2 = 2\pi \cdot T \cdot n \text{ for a motor and } P_1 = 2\pi \cdot T \cdot n \text{ for a generator.} \qquad (22)$$

where

$$P_{fw} = P_{fw0} \cdot (1-s)^{2{,}5} \text{ with } s = 1 - \frac{p \times n}{f} \qquad (23)$$

are the corrected friction and windage losses.

6.1.3.2.6.2 Smoothing of the residual loss data

The residual loss data shall be smoothed by using the linear regression analysis (see Figure 5) based on expressing the losses as a function of the square of the load torque according to the relationship:

$$P_{Lr} = A \times T^2 + B \qquad (24)$$

A and B are constants determined from the six load points using the following formulas:

A is the slope according to

$$A = \frac{i \cdot \sum\left(P_{Lr} \cdot T^2\right) - \sum P_{Lr} \cdot \sum T^2}{i \cdot \sum\left(T^2\right)^2 - \left(\sum T^2\right)^2} \qquad (25)$$

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B is the intercept according to

$$B = \frac{\sum P_{Lr}}{i} - A \cdot \frac{\sum T^2}{i} \tag{26}$$

i is the number of load points summed.

The intercept B should be considerably smaller (< 50 %) than the additional load losses P_{LL} at rated torque. Otherwise the measurement may be erroneous and should be checked.

NOTE The intercept B may be positive or negative. Figure 5 shows an example for positive intercept B.

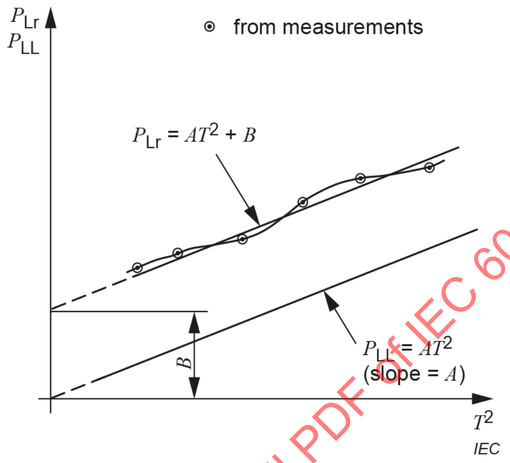

Figure 5 – Smoothing of the residual loss data

The correlation coefficient is calculated as

$$\gamma = \frac{i \cdot \Sigma\left(P_{Lr} \cdot T^2\right) - \left(\Sigma P_{Lr}\right) \cdot \left(\Sigma T^2\right)}{\sqrt{\left(i \cdot \Sigma\left(T^2\right)^2 - \left(\Sigma T^2\right)^2\right) \cdot \left(i \cdot \Sigma P_{Lr}^2 - \left(\Sigma P_{Lr}\right)^2\right)}} \tag{27}$$

~~When~~ If the correlation coefficient γ is less than 0,95, delete the worst point and repeat the regression. If γ increases to ≥ 0,95, use the second regression; if γ remains less than 0,95, the test is unsatisfactory and errors in the instrumentation or test readings, or both, are indicated. The source of the error should be investigated and corrected, and the test should be repeated. In case of sufficient test data, a correlation coefficient of 0,98 or better is likely.

~~When~~ If the slope constant A is established, a value of additional load losses for each load point shall be determined by using the formula:

$$P_{LL} = A \times T^2 \tag{28}$$

6.1.3.3 Efficiency determination

6.1.3.3.1 Total losses

The total losses shall be taken as the sum of the adjusted iron losses, the corrected friction and windage losses, the load losses and the additional load losses:

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$$P_{\text{T}} = P_{\text{fe}} + P_{\text{fw}} + P_{\text{s}\,\theta} + P_{\text{r}\,\theta} + P_{\text{LL}}\,, \tag{29}$$

where

$$P_{\text{fw}} = P_{\text{fw0}} \cdot (1 - s_{\theta})^{2,5} \tag{30}$$

are the corrected friction and windage losses.

6.1.3.3.2 Efficiency

The efficiency is determined from

$$\eta = \frac{P_{1,\theta} - P_{\text{T}}}{P_{1,\theta}} = \frac{P_2}{P_2 + P_{\text{T}}} \tag{31}$$

NOTE Usually, the first expression is preferred for a motor, the second one for a generator.

where

$P_{1,\theta}$ is the temperature corrected input power from the rated load test;

P_2 is the output power from the rated load test.

6.1.4 Method 2-1-1C – Summation of losses with additional load losses from assigned allowance

6.1.4.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. For the reason that full load testing as required by method 2-1-1B is in general not practical for ratings above 2 MW, this method is based on a load test with reduced voltage and an assigned value for the additional load losses. Therefore the full load test and the load curve test are not required for method 2-1-1C.

Apart from this, method 2-1-1C is similar to method 2-1-1B.

For an overview, Figure 6 provides a flowchart for efficiency determination by this test method.

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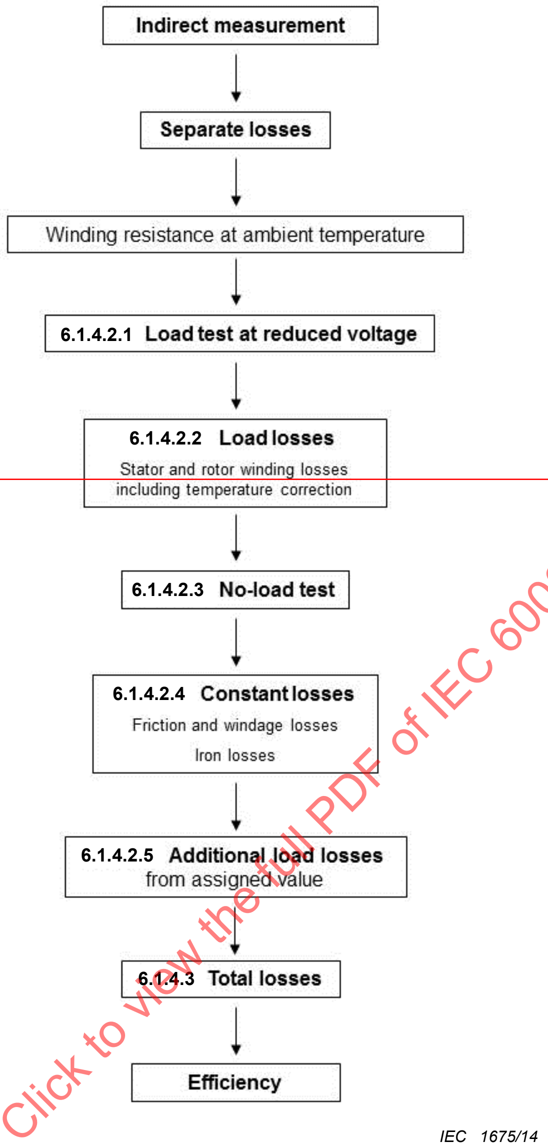

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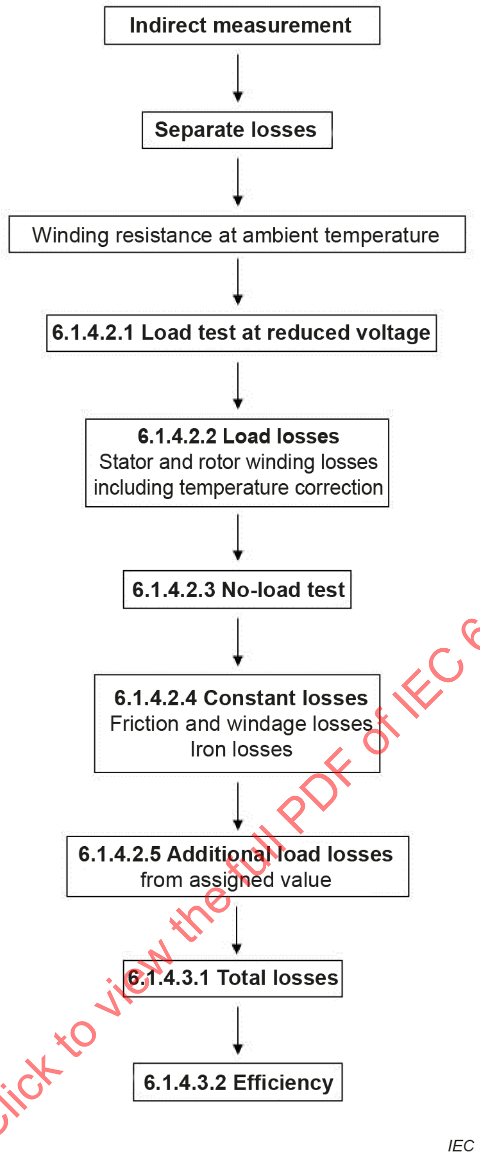

Figure 6 – Efficiency determination according to method 2-1-1C

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6.1.4.2 Test procedure

6.1.4.2.1 Load test at reduced voltage

For large machines which cannot be tested at full load, the load test at reduced voltage is an appropriate method. The following are required: a load test with the machine acting as a motor at reduced voltage U_{red} at rated speed, a no-load test at the same reduced voltage U_{red}, and a no-load test at rated voltage and rated frequency.

Using this method, it is assumed that at reduced voltage, while keeping the speed constant, currents diminish as the voltage and power diminishes as the square of the voltage.

Operate the machine using the maximum available load with a decrease in voltage to achieve rated speed. Operate to achieve thermal equilibrium.

At reduced voltage, record: U_{red}, I_{red}, P_{1red}, I_{0red}, $\cos(\varphi_{0red})$.

At rated voltage and no-load, record: U_N, I_0, $\cos(\varphi_0)$.

From the result of such a test calculate the current under load and the absorbed power at rated voltage:

$$\underline{I} = \underline{I}_{red} \frac{U_N}{U_{red}} + \Delta \underline{I}_0 \quad (32)$$

where

$$\Delta \underline{I}_0 = -j(|\underline{I}_0| \sin \varphi_0 - |\underline{I}_{0,red}| \frac{U_N}{U_{red}} \sin \varphi_{0,red}) \quad (33)$$

$$P_1 = P_{1,red} \times \left(\frac{U_N}{U_{red}} \right)^2 \quad (34)$$

NOTE Underlined current symbols indicate vectors (see Figure 7).

By means of the values I and P_1 thus determined, and with the slip measured at reduced voltage, it is possible to calculate the load losses, similar to a load test at rated voltage.

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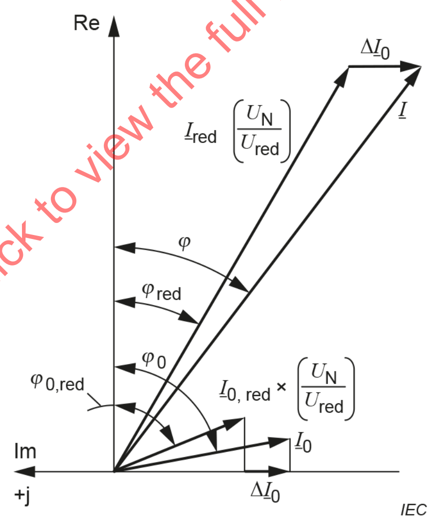

Figure 7 – Vector diagram for obtaining current vector from reduced voltage test

6.1.4.2.2 Load losses

The determination of load losses is similar to 6.1.3.2.2.

6.1.4.2.3 No-load test

The no-load test shall be carried out on a hot machine immediately after the load test.

The no-load test is similar to 6.1.3.2.4.

6.1.4.2.4 Constant losses

The determination of the constant losses is similar to 6.1.3.2.5.

6.1.4.2.5 Additional load losses P_{LL}

The value of additional load losses P_{LL} at rated load shall be determined as a percentage of input power P_1 using the curve in Figure 8.

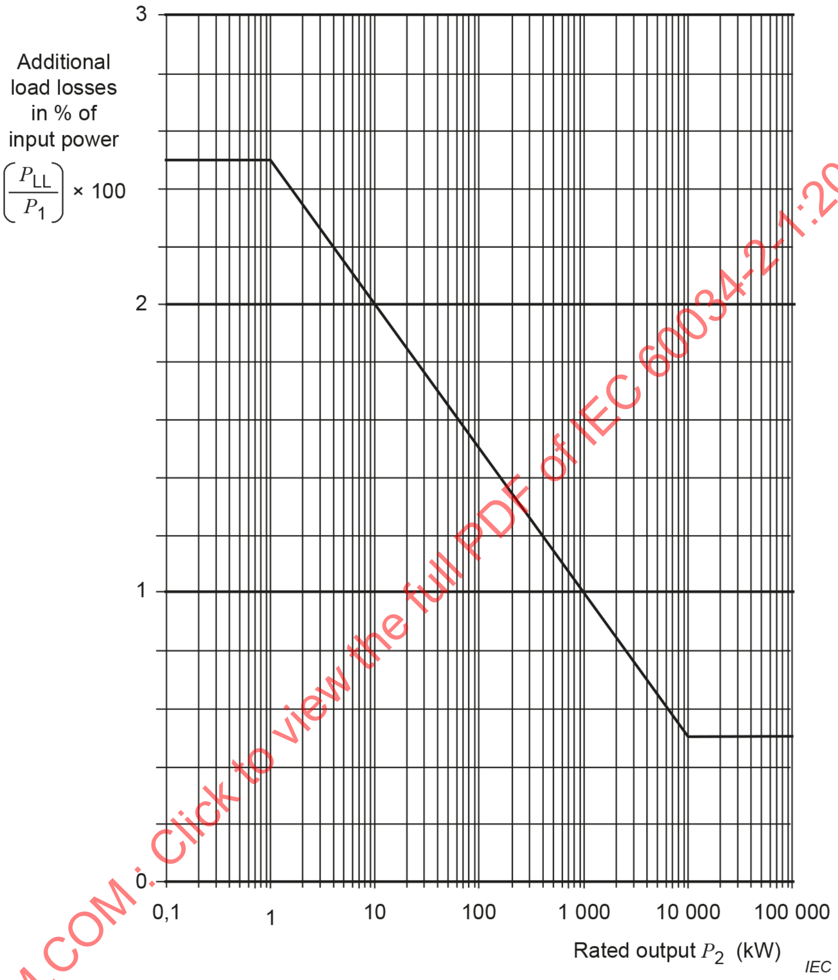

Figure 8 – Assigned allowance for additional load losses P_{LL}

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The values of the curve may be described by the following formulas:

for $P_2 \leq 1$ kW $\quad P_{LL} = P_1 \times 0{,}025$

for 1 kW < P_2 < 10 000 kW $\quad P_{LL} = P_1 \times \left[0{,}025 - 0{,}005 \log_{10}\left(\frac{P_2}{1\,\text{kW}}\right)\right]$

for $P_2 \geq 10\,000$ kW $\quad P_{LL} = P_1 \times 0{,}005$

For other than rated loads, it shall be assumed that the additional load losses vary as the square of the primary current minus the square of the no-load current:

$$P_{\mathrm{LL}}(I) = P_{\mathrm{LL}}(I_{\mathrm{N}}) \times \frac{I^2 - I_0^2}{I_{\mathrm{N}}^2 - I_{0\mathrm{N}}^2}$$

NOTE The curve does not represent an average but an upper envelope of a large number of measured values, and may in most cases yield greater additional load losses than 6.1.3.

6.1.4.3 Efficiency determination

6.1.4.3.1 Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_{\mathrm{T}} = P_{\mathrm{c}} + P_{\mathrm{s}} + P_{\mathrm{r}} + P_{\mathrm{LL}} \quad (35)$$

6.1.4.3.2 Efficiency

The efficiency is determined from

$$\eta = \frac{P_1 - P_{\mathrm{T}}}{P_1} = \frac{P_2}{P_2 + P_{\mathrm{T}}} \quad (36)$$

NOTE Usually, the first expression is preferred for a motor, the second one for a generator.

6.2 Testing methods for field or routine-testing

6.2.1 General

These test methods may be used for any test, i.e. field-tests, customer-specific acceptance tests or routine-tests.

In addition, preferred methods of Table 2 may also be used outside the power range identified in Table 2.

Methods defined by this document are given in Table 3.

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Table 3 – Induction machines: other methods

Reference	Method	Description	Subclause	Required facility
2-1-1D	Dual-supply-back-to-back	Dual-supply, back-to-back test	6.2.2	Machine set for full-load; two identical units
2-1-1E	Single-supply-back-to-back	Single-supply, back-to-back test	6.2.3	Two identical units (wound rotor)
2-1-1F	Reverse rotation	P_{LL} from removed rotor and reverse rotation test	6.2.4	Auxiliary motor with rated power up to 5 × total losses
2-1-1G	Eh-star	P_{LL} from Eh-star test	6.2.5	Winding shall be connected in star connection.
2-1-1H	Equivalent circuit	Currents, powers and slip from the equivalent circuit method, P_{LL} from assigned value	6.2.6	If test equipment for other tests is not available (no possibility of applying rated load, no duplicate machine)

6.2.2 Method 2-1-1D – Dual supply back-to-back-test

6.2.2.1 General

For an overview, Figure 9 provides a flowchart for efficiency determination by this test method.

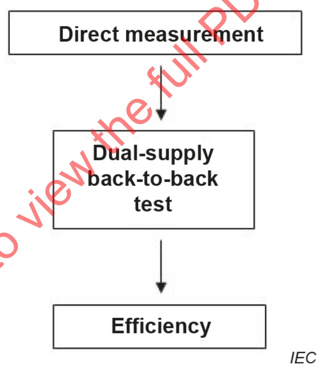

Figure 9 – Efficiency determination according to method 2-1-1D

6.2.2.2 Test procedure

Mechanically, couple two identical machines together (see Figure 10).

Tests are made with the power supplies exchanged but with the instruments and instrument transformers remaining with the same machine.

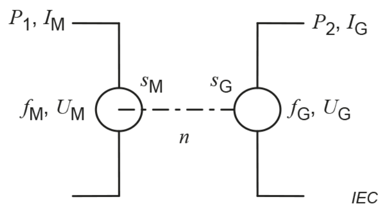

Figure 10 – Sketch for dual supply back-to-back test

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Connect the driven machine (induction generator) terminals to either a machine set or a converter, supplying reactive power and absorbing active power. Supply one machine (the motor for motor rating, the generator for generator rating) with rated voltage and frequency; the second one shall be supplied with a frequency lower than that of the first machine for generator operation or higher for motor operation. The voltage of the second machine shall be that required to result in the rated voltage-to-frequency ratio.

Reverse the motor and generator connections and repeat the test.

For each test, record:

– U_M, I_M, P_1, f_M, s_M for the motor;

– U_G, I_G, P_2, f_G, s_G for the generator;

– θ_c.

6.2.2.3 Efficiency determination

~~When~~ If identical machines are run at essentially the same rated conditions, the efficiency shall be calculated from half the total losses and the average of motor input power ~~of the motor~~ and generator output power as follows:

$$\eta = 1 - \frac{P_T}{\frac{P_1 + P_2}{2}} \qquad (37)$$

where

$$P_T = \frac{1}{2}(P_1 - P_2) \qquad (38)$$

6.2.3 Method 2-1-1E – Single supply back-to-back-test

6.2.3.1 General

For an overview, Figure 11 provides a flowchart for efficiency determination by this test method.

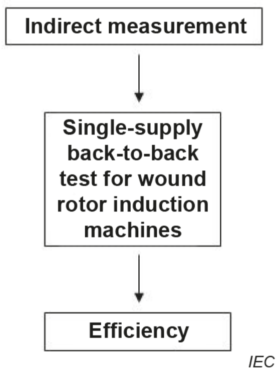

Figure 11 – Efficiency determination according to method 2-1-1E

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6.2.3.2 Test procedure

This test is applicable to wound-rotor induction machines. Mechanically couple two identical machines together and connect them both electrically to the same power supply so as to operate at rated speed and rated voltage, one as a motor and the other as a generator.

The rotor winding of the motor shall be short-circuited and the rotor winding of the generator shall be connected to a polyphase supply suitable to deliver rated rotor current at slip-frequency. The desired motor-power will be achieved by adjusting frequency and current of the lower frequency power supply.

For each test, record:

– U_1, P_1, I_1 of the power-frequency supply;

– U_r, I_r, P_r of the low-frequency supply;

– P_M absorbed at the motor terminals;

– P_G delivered at the generator terminals;

– θ_c.

6.2.3.3 Efficiency determination

~~When~~ If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

Calculate the efficiency from

$$\eta = 1 - \frac{P_T}{P_M} \quad (39)$$

where

P_M is the power absorbed at the terminals of the machine acting as motor;

P_T is the total losses, defined as half the total absorbed, for wound-rotor induction machines as follows: $P_T = \frac{1}{2}(P_1 + P_r)$

6.2.4 Method 2-1-1F – Summation of losses with additional load losses determined by test with rotor removed and reverse rotation test

6.2.4.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. But in this case the additional load losses are determined by a combination of two individual tests: the test with rotor removed and the reverse rotation test. Apart from that, method 2-1-1F is similar to method 2-1-1B.

For an overview, Figure 12 provides a flowchart for efficiency determination by this test method.

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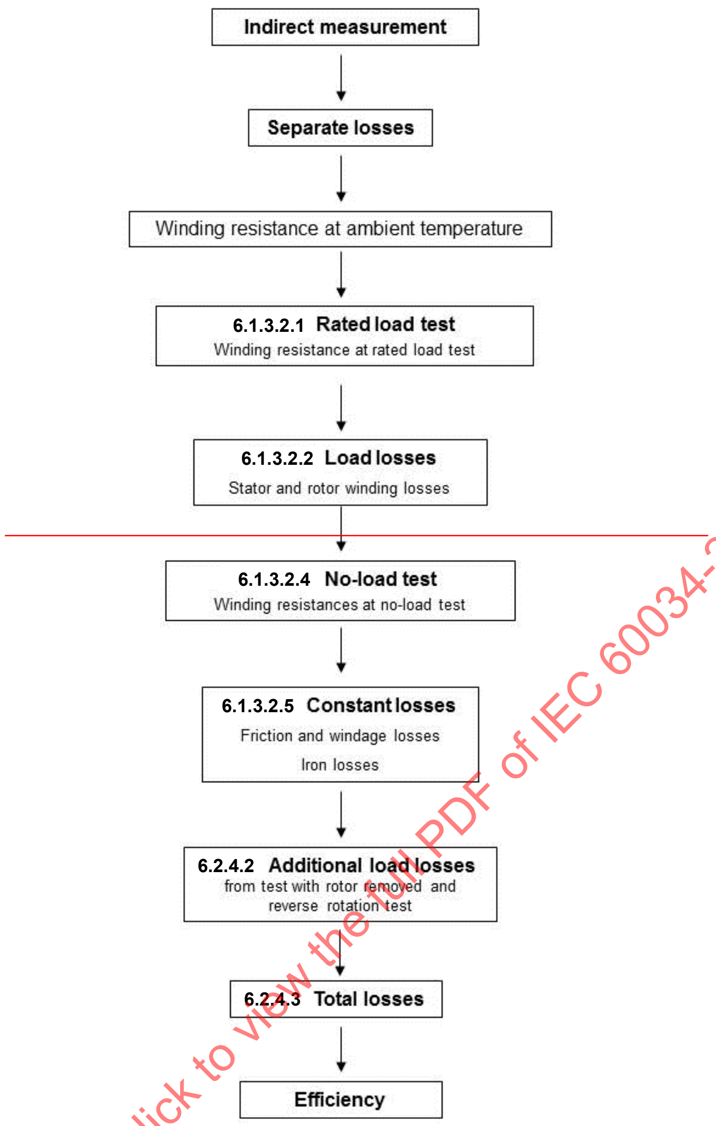

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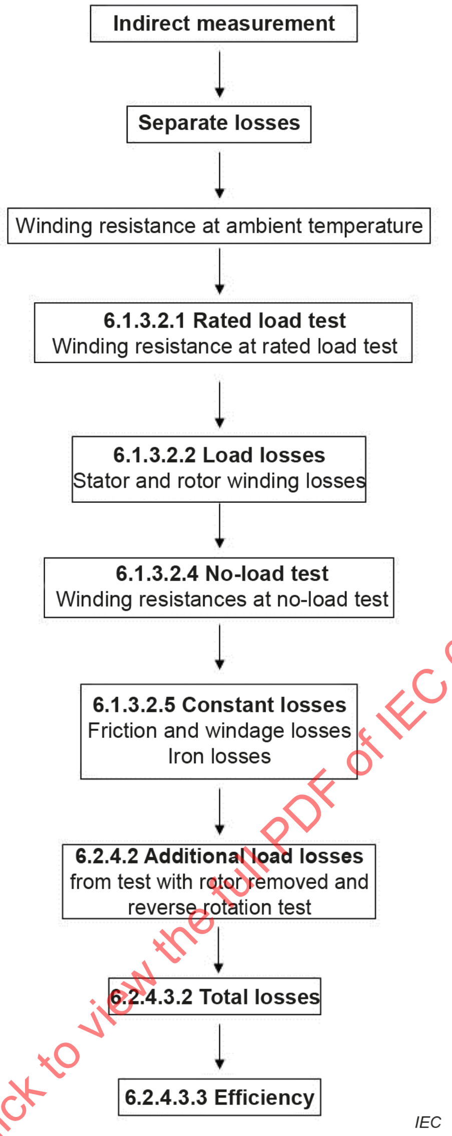

Figure 12 – Efficiency determination according to method 2-1-1F

6.2.4.2 Test procedure

Apart from the determination of the additional load losses, the same procedures as in 6.1.3.2 shall be applied, except that the torque does not need to be measured ~~nor recorded~~.

The required combination of tests for the determination of the additional load losses is as follows:

a) with the rotor removed (for the fundamental frequency additional losses);

b) with the machine rotating at synchronous speed opposite to the magnetic field, driven by external means (for the higher frequencies losses).

During both tests, the stator shall be supplied by a balanced polyphase current of rated frequency for four currents between 25 % and 100 % rated current, and two currents above and of not more than 150 % rated current. Calculate the (rotor) load current I_L:

$$I_L = \sqrt{I^2 - I_0^2} \qquad (40)$$

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where

I is the value of stator current during the test giving a desired load current;

I_0 is the no-load current at rated voltage.

NOTE Due to lack of cooling, the current is usually limited to 125 % or 115 % for 2-pole machines to reduce the risk of overheating.

6.2.4.2.1 Test with the rotor removed

For this test, all parts in which eddy currents might be induced, for example end shields and bearing parts, shall be in place. Apply load current.

For each load current, record (symbols indexed "rm"): $P_{1,rm}$, $I_{L,rm}$, R_{rm}, $\theta_{w,rm}$.

6.2.4.2.2 Reverse-rotation test

For this test, couple a completely assembled machine to a driving motor with an output capability of not less than rated total loss and not more than five times the rated losses of the machine to be tested. ~~When a dynamometer is used for the determination of the shaft power, its maximum torque shall not exceed ten times the torque corresponding to the rated total loss of the machine to be tested.~~ For wound-rotor machines, the rotor terminals shall be short-circuited.

Drive the machine under test at synchronous speed in the direction reverse to the rotation when fed in normal phase sequence:

a) without voltage applied to the stator until friction losses are stabilized. Record: $P_{0,rr}$ supplied by the driving machine at I = 0;

b) with voltage applied to the stator to obtain stator current values equal to those for the test with rotor removed. For all test currents, record (symbols indexed "rr"): $I_{L,rr}$, R_{rr}, $P_{1,rr}$;$\theta_{w,rr}$ for the test motor; $P_{D,rr}$ of the drive motor.

~~NOTE~~ The low power factor of the tests may require a phase error correction to all wattmeter readings.

6.2.4.3 Efficiency determination

6.2.4.3.1 Additional load losses

Smooth the test values of the stator powers $P_{1,rm}$ and $P_{1,rr}$, and the shaft power $\left(P_{D,rr} - P_{0,rr}\right)$ by applying a regression analysis to the log of powers and currents, resulting in the relationships below:

$$P_{1,rm} = A_{rm} \times I^{N1} + B_{L,rm}; \quad P_{1,rr} = A_{rr} \times I^{N2} + B_{L,rr}; \quad \left(P_{D,rr} - P_{0,rr}\right) = A_{D,rr} \times I^{N3} + B_{D,rr} \tag{41}$$

The smoothed powers will then be as follows:

$$P_{1,rm} = A_{rm} \times I^{N1}; \quad P_{1,rr} = A_{rr} \times I^{N2}; \quad \left(P_{D,rr} - P_{0,rr}\right) = A_{D,rr} \times I^{N3} \tag{42}$$

If the data are accurate, each curve will show a close square-law relationship between power and current.

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The additional load losses are: $P_{LL} = P_{LL,rm} + P_{LL,rr}$ where for each test current:

$$P_{LL,rm} = P_{1,rm} - \left(3 \times I^2 \times R_{s,rm}\right) \text{ is the fundamental frequency loss} \tag{43}$$

where

$R_{s,rm}$ is the stator phase resistance referred to the average of the temperatures $\theta_{W,rm}$;

$P_{LL,rr} = \left(P_{D,rr} - P_{0,rr}\right) - \left(P_{1,rr} - P_{LL,rm} - \left(3 \times I^2 \times R_{s,rr}\right)\right)$ is the higher frequencies loss

where

$R_{s,rr}$ is the stator phase resistance referred to the average of the temperatures $\theta_{W,rr}$.

The additional load loss at a specified operating point can be determined in the following steps.

a) Calculate an approximate value for the rated load current I_{NL} corresponding to the rated value of stator line current:

$$I_{NL} = \sqrt{I_N^2 - I_0^2} \tag{44}$$

where

I_N is the rated value of stator line current;

I_0 is the value of no-load stator current.

For the value of load current I_{NL}, calculate a rated value of stray load loss P_{NLL} as follows:

$$P_{NLL} = A_{Drr} \times I_{NL}^{N3} + 2A_{rm} \times I_{NL}^{N1} - A_{rr} \times I_{NL}^{N2} - 6I_{NL}^2 \times \left(R_{srm} - 0{,}5R_{srr}\right) \tag{45}$$

b) Calculate the value of load current I_L at any operating point:

$$I_L = \sqrt{I^2 - I_0^2} \tag{46}$$

where

I is the stator line current at the operating point.

c) Calculate the stray load loss P_{LL} at the operating point:

$$P_{LL} = P_{NLL} \times \left(\frac{I_L}{I_{NL}}\right)^2 \tag{47}$$

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6.2.4.3.2 Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_T = P_c + P_s + P_r + P_{LL} \quad (48)$$

6.2.4.3.3 Efficiency

The efficiency is determined from

$$\eta = \frac{P_1 - P_T}{P_1} = \frac{P_2}{P_2 + P_T} \quad (49)$$

where

P_1 is the input power from a rated load test;

P_2 is the output power.

6.2.5 Method 2-1-1G – Summation of losses with additional load losses determined by Eh-star method

6.2.5.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. But in this case the additional load losses are determined by the Eh-star test. Apart from that, method 2-1-1G is similar to method 2-1-1B.

For an overview, Figure 13 provides a flowchart for efficiency determination by this test method.

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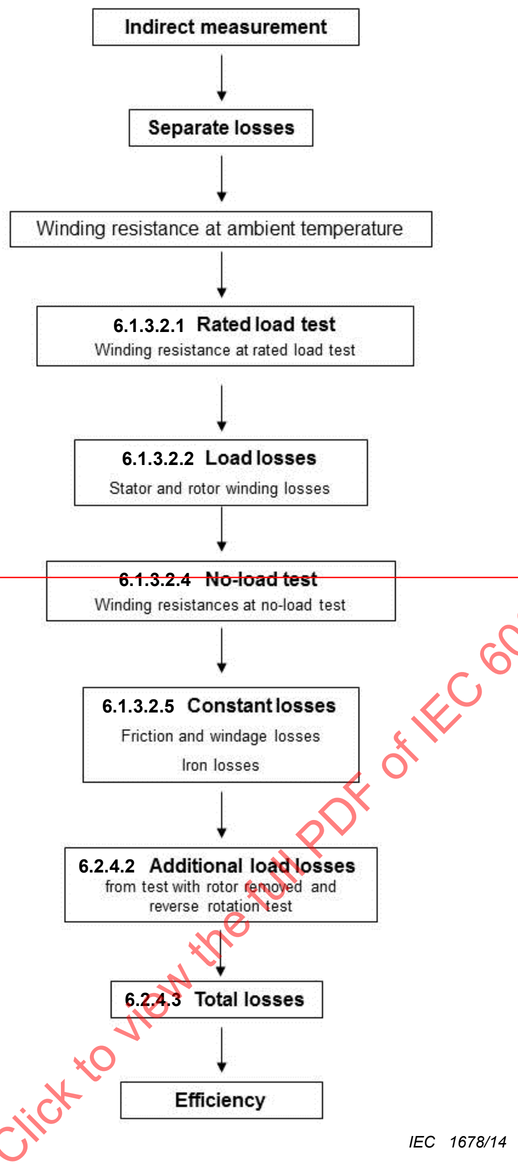

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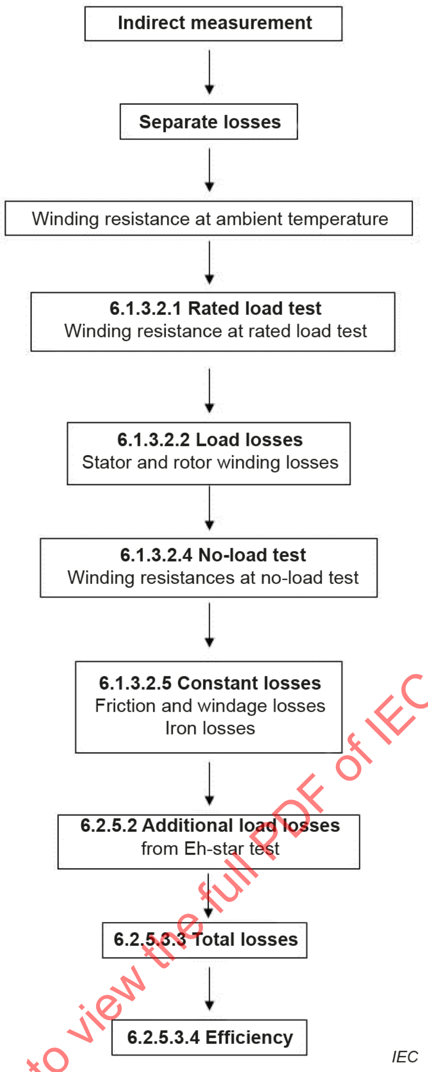

Figure 13 – Efficiency determination according to method 2-1-1G

6.2.5.2 Test procedure

Apart from the determination of the additional load losses, the same procedures as in 6.1.3.2 shall be applied.

The procedure for the determination of the additional load losses requires operating the uncoupled motor with unbalanced voltage supply. The test circuit is according to Figure 14.

Motors rated for and connected in delta-connection shall be reconnected to star-connection during this test. The star-point shall not be connected to system neutral or earth, to avoid zero-sequence currents.

The third motor-phase shall be connected to the power-line by means of a resistor R_{eh} (see Figure 14) having approximately the following typical value:

for motors rated for star-connection: $$R'_{eh} = \frac{U_N}{\sqrt{3} \cdot I_N} \cdot 0,2 \qquad (50)$$

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for motors rated for delta-connection: $$R'_{\text{eh}} = \frac{\sqrt{3} \cdot U_{\text{N}}}{I_{\text{N}}} \cdot 0{,}2 \qquad (51)$$

The resistor R_{eh} used during the test shall be adjusted so that the positive sequence current $I_{(1)}$ stays below 30 % of negative sequence current $I_{(2)}$ and the speed stays in the range of typical motor speeds near rated speed (see below). It is recommended to begin the test with an actual resistor R_{eh} that differs no more than 20 % from the typical value R'_{eh}.

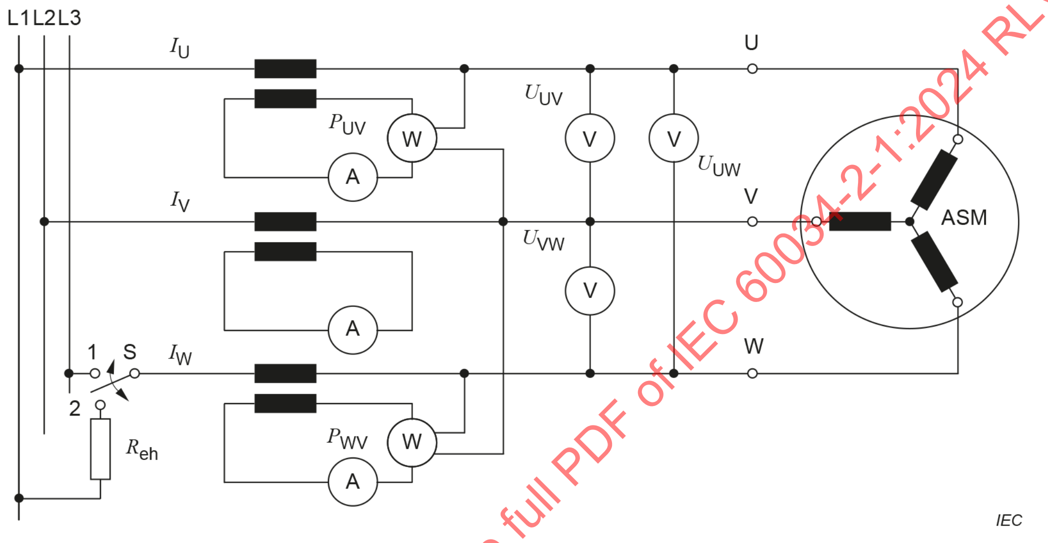

Figure 14 – Eh-star test circuit

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Test current I_{t} is given by

for motors rated for star-connection: $$I_{\text{t}} = \sqrt{I_{\text{N}}^2 - I_0^2} \qquad (52)$$

for motors rated for delta-connection: $$I_{\text{t}} = \frac{\sqrt{I_{\text{N}}^2 - I_0^2}}{\sqrt{3}} \qquad (53)$$

Test voltage U_{t} is given by

for motors rated for star-connection: $$U_{\text{t}} = U_{\text{N}} \qquad (54)$$

for motors rated for delta-connection: $$U_{\text{t}} = U_{\text{N}} \cdot \sqrt{3} \qquad (55)$$

Prior to the test the no-load losses have to be stabilised according to 6.1.3.2.4.

Measure and record the resistance between the terminals V and W (R_{VW}) before and after the complete test.

In order to avoid excessive unequal heating of the three phases, the test shall be conducted on a cold machine and carried out as quickly as possible.

Large motors can only be started without the R_{eh} resistor (switch S to position 1, see Figure 14) at reduced voltage (25 % – 40 % U_N). After run-up connect R_{eh} by switching to position 2.

Small motors should start-up with resistor R_{eh} already connected. In this case, the switch is not needed.

Vary the supply voltage for six test points. The test points shall be chosen to be approximately equally spaced between 150 % and 75 % of rated phase current measured in phase V (I_V). When starting the test, begin with the highest current and proceed in descending order to the lowest current.

The line-to-line resistance R_{VW} for 100 % test current and lower currents shall be the value determined after the lowest reading (at the end of the test). The resistance used for currents higher than 100 % shall be determined as being a linear function of current, using the readings before and after the complete test. The test resistance is determined using the extrapolation according to 5.7.1.

Record for each test point: I_U, I_V, I_W, U_{UV}, U_{VW}, U_{WU}, P_{UV}, P_{WV}, n .

It is understood that in this test no averaging of phase resistances is permissible.

NOTE Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each load point may then be determined from the temperature of the winding at that point in relation to the resistance and temperature measured before the start of the test.

Some commonly used integrated wattmeters symmetrize the three phases by an internal virtual star connection. However, in this test the power supply is intentionally unsymmetrical. Therefore, it is essential to ensure that neither earthing of the star point nor a virtual star point is established. The provided test circuit (see Figure 14) should be strictly applied.

In order to achieve accurate results the slip shall be not greater than twice the rated slip for all currents, in other words: $n > n_{syn} - 2 \cdot (n_{syn} - n_N)$. If this condition cannot be met the test shall be repeated with an increased value of R_{eh}. If the motor still runs unstable at currents below 100 % of rated phase current these test points should be omitted.

6.2.5.3 Efficiency determination

6.2.5.3.1 Additional load losses

For each test point calculate the values using the formulas in Annex A.

6.2.5.3.2 Smoothing of the additional-load loss data

The additional-load loss data shall be smoothed by using the linear regression analysis (see Figure 5).

The losses shall be expressed as a function of the square of the negative sequence current $I_{i(2)}$ related to test current I_t:

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$$P_{Lr} = A \cdot \left(\frac{I_{i(2)}}{I_t} \right)^2 + B \tag{56}$$

A and B shall be computed similar to the procedure described in 6.1.3.2.6.

When the slope constant A is established, the value of additional load losses for rated load shall be determined by using the formula $P_{LL} = A \times T^2$.

6.2.5.3.3 Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_T = P_c + P_s + P_r + P_{LL} \tag{57}$$

6.2.5.3.4 Efficiency

The efficiency is determined from

$$\eta = \frac{P_1 - P_T}{P_1} = \frac{P_2}{P_2 + P_T} \tag{58}$$

NOTE Usually, the first expression is preferred for a motor, the second one for a generator.

where

P_1 is the input power from a rated load test;

P_2 is the output power.

6.2.6 Method 2-1-1H – Determination of efficiency by use of the equivalent circuit parameters

6.2.6.1 General

This method may be applied ~~when~~ if a load test is not possible. It is based on the conventional T-model per-phase circuit of an induction machine, including an equivalent iron-loss resistor parallel to the main field reactance (see Figure 15). The rotor side parameters and quantities are referred to the stator side; this is indicated by the presence of an apostrophe ‘ at the symbols for example $X'_{\sigma r}$.

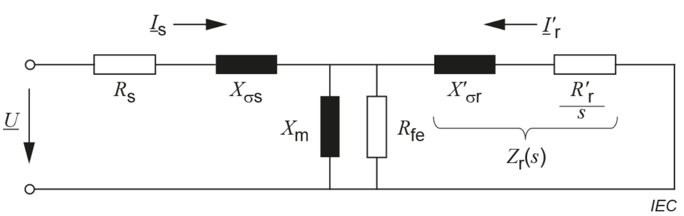

Figure 15 – Induction machine, T-model with equivalent iron loss resistor

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Application of the method to cage induction machines requires the following designed values to be available.

– $\frac{X_{\sigma s}}{X'_{\sigma r}}$ ratio of stator leakage reactance to rotor leakage reactance.

– α_r temperature coefficient of the rotor windings (conductivity referred to 0 °C).

– $X_{\sigma s}, X_m$ stator leakage and magnetizing reactances.

NOTE 1 When using the equivalent circuit method, all voltages, currents and impedances are per phase values for a three-phase machine in Y-connection; active and reactive powers are per complete machine.

NOTE 2 For copper α_r = 1/235 and for aluminium α_r = 1/225.

For an overview, Figure 16 provides a flowchart for efficiency determination by this test method.

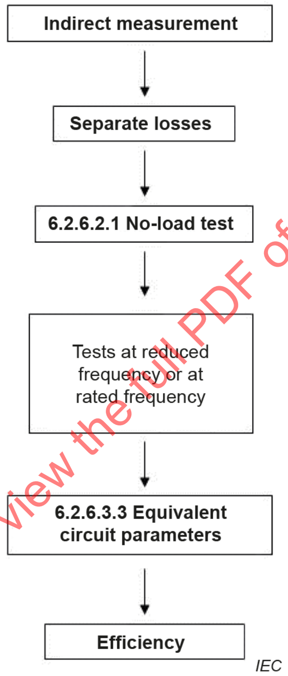

Figure 16 – Efficiency determination according to method 2-1-1H

6.2.6.2 Test procedure

6.2.6.2.1 No-load test

The no-load losses shall be stabilized at rated frequency and voltage.

The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

6.2.6.2.2 Tests at reduced frequency

With the rotor of the machine locked, supply power from a three-phase, adjustable-frequency converter capable of furnishing up to 25 % of the rated frequency at rated current. An average value of impedance shall be obtained from the position of the rotor relative to the stator.

During the tests the frequency converter, either a machine set or a static converter, should supply practically sinusoidal current at the output.

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The rotor windings of wound-rotor machines should be short-circuited for the test.

Supply rated current and take readings for at least three frequencies, including one at less than 25 % and the others between 25 % and 50 % rated frequency. During this quick test the stator winding temperature increase should not exceed 5 K.

For at least three frequencies, record: U, I, f, P_1, R_s, θ_c, θ_w.

6.2.6.2.3 Tests at rated frequency

Impedance values can also be determined from the following tests.

a) Reactance from a rated frequency, reduced voltage, rated current locked rotor test: record voltage, current, power, frequency and temperatures.
b) Rotor running resistance:
   1) from a stabilized rated frequency, rated voltage reduced load test. Record voltage, power, current, slip and temperatures for the load point; or
   2) from an open-circuit test, following a stabilized rated frequency, rated voltage no-load operation. Record the open-circuit voltage and winding temperature as a function of time after the motor is tripped from a no-load test.

NOTE This test assumes relatively low current displacement in the rotor.

6.2.6.3 Efficiency determination

6.2.6.3.1 Values from measurements

The method is based on the T-model circuit (see Figure 15).

NOTE When using the equivalent circuit method, all voltages, currents and impedances are per phase values for a three-phase machine in Y-connection; active powers and reactive powers are per complete machine.

The procedure described in this subclause is based on the test with reduced frequency. When using the test with rated frequency notice the following deviations:

a) the reactances are calculated in the same manner as in the following;
b) the rotor running resistance is determined:
   – using the test at rated frequency described in b) by reverse calculation using the equivalent circuit in Figure 15, assuming a value for R_r'. Adjust the value of R_r' until the calculated power is within 0,1 % of the measured power, or the calculated current is within 0,1 % of the measured current;
   – using the test at rated frequency described in b) by determining the time constant from the slope of the plot of the decaying voltage and the time on the open-circuit test. Determine R_r' from the formula:

$$R_r' = \frac{\left(X_m + X'_{\sigma r}\right)}{2\pi f \tau_0} \qquad (59)$$

where

X_m is the magnetizing reactance;

$X'_{\sigma r}$ is the rotor leakage reactance;

f is the line frequency;

τ_0 is the open-circuit time constant.

Correct the value of R_r' to the operating temperature from the test temperature.

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6.2.6.3.2 Determine the reactive powers

– from the no-load test at rated voltage $U_0 = U_N$ and rated frequency

$$P_{Q,0} = \sqrt{(3U_0 I_0)^2 - P_0^2} \tag{60}$$

– from the locked rotor test at reduced frequency

$$P_{Q,lr} = \sqrt{(3U\,I)^2 - P_1^2} \tag{61}$$

where

U_0, I_0 and P_0 are phase voltage, phase current and supplied power from the no-load test at rated terminal voltage;

U, I and P_1 are phase voltage, phase current and supplied power from the locked rotor impedance test at the frequencies f of this test.

6.2.6.3.3 Equivalent circuit parameters

6.2.6.3.3.1 General

The equivalent circuit parameters are determined in the following steps.

6.2.6.3.3.2 Reactances

Calculate the reactances X_m from the no-load test and $X_{\sigma s,lr}$ from the locked-rotor test at 25 % rated frequency:

$$X_m = \frac{3U_0^2}{P_{Q,0} - 3I_0^2 X_{\sigma s}} \times \frac{1}{\left(1 + \frac{X_{\sigma s}}{X_m}\right)^2} \qquad X_{\sigma s,lr} = \frac{P_{Q,lr}}{3I^2\left(1 + \frac{X_{\sigma s}}{X'_{\sigma r}} + \frac{X_{\sigma s}}{X_m}\right)} \times \left(\frac{X_{\sigma s}}{X'_{\sigma r}} + \frac{X_{\sigma s}}{X_m}\right) \tag{62}$$

$$X_{\sigma s} = \frac{f_N}{f_{lr}} X_{\sigma s,lr} \qquad X'_{\sigma r} = \frac{X_{\sigma s}}{X_{\sigma s} / X'_{\sigma r}} \tag{63}$$

Calculate using designed values as start values.

$$X_{\sigma s}, X_m \text{ and } \frac{X_{\sigma s}}{X'_{\sigma r}} \tag{64}$$

Recalculate until X_m and $X_{\sigma s}$ deviate less than 0,1 % from the values of the preceding step.

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6.2.6.3.3.3 Iron loss resistance

Determine the resistance per phase equivalent to the iron losses at rated voltage from

$$R_{fe} = \frac{3U_{N,ph}^2}{P_{fe}} \times \frac{1}{\left(1+\frac{X_{\sigma s}}{X_m}\right)^2} \tag{65}$$

where

P_{fe} is the iron losses according to the procedure given in 6.1.3.2.5 from P_0 at rated voltage.

6.2.6.3.3.4 Rotor resistance

Determine the uncorrected rotor resistance for each locked rotor impedance test point:

$$R'_{r,lr} = \left(\frac{P_1}{3I^2} - R_s\right) \times \left(1+\frac{X'_{\sigma r}}{X_m}\right)^2 - \left(\frac{X'_{\sigma r}}{X_{\sigma s}}\right)^2 \times \frac{X_{\sigma s,lr}^2}{R_{fe}} \tag{66}$$

where

R_s is the stator winding resistance per phase at the corresponding temperature θ_W.

NOTE If the rotor winding temperature deviates much from the stator winding temperature the method will become inaccurate.

The rotor resistance corrected to reference temperature (see 5.7.2, and Table 1) is, for each locked rotor impedance test frequency, given by

$$R''_{r,lr} = R'_{r,lr} \times \frac{1+\alpha_r\theta_{ref}}{1+\alpha_r\theta_W} \tag{67}$$

Plot a curve of $R''_{r,lr}$ values against frequency f_{lr}. The intercept with f_{lr} = 0 results in the stator referred rotor resistance R'_r.

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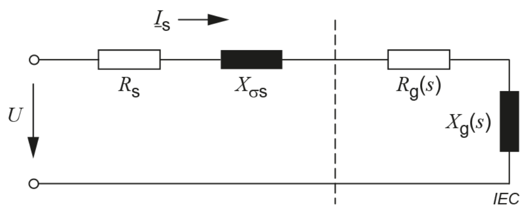

Figure 17 – Induction machines, reduced model for calculation

6.2.6.3.3.5 Load dependent impedances

For each desired load point intermediate, calculate slip dependent impedance and admittance values (see Figure 17):

$$Z_r = \sqrt{\left(\frac{R_r'}{s}\right)^2 + X_{\sigma r}'^2} \qquad Y_g = \sqrt{\left(\frac{R_r'/s}{Z_r^2} + \frac{1}{R_{fe}}\right)^2 + \left(\frac{X_{\sigma r}'}{Z_r^2} + \frac{1}{X_m}\right)^2}$$

$$R_g = \frac{\frac{R_r'/s}{Z_r^2} + \frac{1}{R_{fe}}}{Y_g^2} \qquad X_g = \frac{\frac{X_{\sigma r}'}{Z_r^2} + \frac{1}{X_m}}{Y_g^2} \tag{68}$$

Calculate the resulting impedance seen from the terminals:

$$R = R_s + R_g \qquad X = X_{\sigma s} + X_g \qquad Z = \sqrt{R^2 + X^2} \tag{69}$$

where

s is the estimated slip;

R_s is the stator winding resistance per phase at reference temperature θ_{ref}.

6.2.6.3.4 Currents and losses

The performance values are determined in the following steps. Determine:

$I_s = \frac{U_N}{Z}$ stator phase current; $I_r' = I_s \frac{1}{Y_g Z_r}$ rotor phase current;

$P_\delta = 3 I_r'^2 \frac{R_r'}{s}$ air gap power transferred to the rotor; $P_{fe} = 3 I_s^2 \frac{1}{Y_g^2 R_{fe}}$ iron loss;

$P_s = 3 I_s^2 R_s$; $P_r = 3 I_r'^2 R_r'$ stator and rotor winding loss;

$P_{LL} = P_{LL,N} \left(\frac{I_r'}{I_{r,N}'}\right)^2$ additional load losses,

from a value $P_{LL,N}$ at rated load, either by assigned value (method C) or measured by the reverse rotation test (method F) or by Eh-star test (method G).

The total losses are:

$$P_T = P_s + P_{fe} + P_r + P_{LL} + P_{fw} \tag{70}$$

Since input and shaft power are $P_1 = 3 I_s^2 R$ and $P_2 = P_1 - P_T$, the slip shall be corrected, and the current and loss calculations shall be repeated until P_2 for motor operation, or P_1 for generator operation, is near enough to the desired value.

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The efficiency (motor~~ing~~ operation) results from:

$$\eta = \frac{P_2}{P_1} \qquad (71)$$

7 Test methods for the determination of the efficiency of synchronous machines

7.1 Preferred testing methods

7.1.1 General

This document defines three different preferred methods with low uncertainty within the given range of application, Table 4 and Table 5. The method to be used depends on the frame size or the rating of the machine under test:

Method 2-1-2A: Direct measurement of input and output power by using a ~~dynamometer~~ torque measuring device. To be applied for all machines with a frame size below or equal 180 mm and for permanent-magnet-excited machines of any rating.

Method 2-1-2B: Summation of separate losses with a full load test and short circuit test for the determination of the additional load losses. To be applied for all machines with a frame size above 180 mm and a rated output power up to 2 MW.

Method 2-1-2C: Summation of separate losses without a full load test. Short circuit test for the determination of the additional load losses. To be applied for all machines with a rated output power greater than 2 MW.

Table 4 – Synchronous machines with electrical excitation: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-2A	Direct measurement: Input-output	Torque measurement	7.1.2	Machine size: $H \leq$ 180	~~Dynamometer~~ Torque measuring device for full-load
2-1-2B	Summation of losses with rated load test and short circuit test	P_{LL} from short circuit test	7.1.3	Machine size: H > 180 and rated output power up to 2 MW	Machine set for full-load
2-1-2C	Summation of separate losses without rated load test and P_{LL} from short circuit test	Excitation current from Potier / ASA / Swedish diagram; P_{LL} from short-circuit test	7.1.4	Rated output power greater than 2 MW	

NOTE In the table, H is the shaft height (distance from the centre line of the shaft to the bottom of the feet), in millimetres (see frame numbers in IEC 60072-1).

Table 5 – Synchronous machines with permanent magnets: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-2A	Direct measurement: Input-output	Torque measurement	7.1.2	All ratings	~~Dynamometer~~ Torque measuring device for full-load

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7.1.2 Method 2-1-2A – Direct measurement of input and output

7.1.2.1 General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the stator is measured in the same test.

This procedure is also applicable for synchronous machines with excitation by permanent magnets.

Input and output power are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 18);

– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

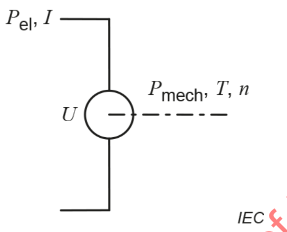
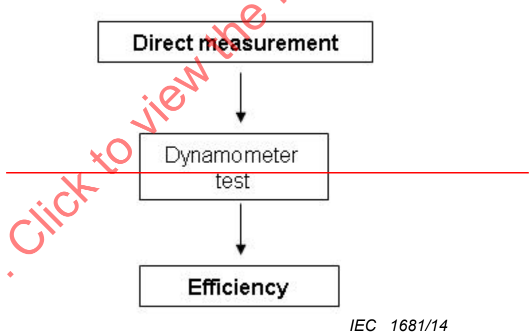


Figure 18 – Sketch for torque measurement test

For an overview, Figure 19 provides a flowchart for efficiency determination by this test method.



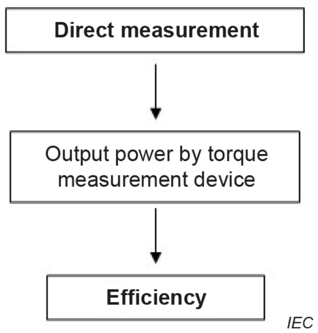


Figure 19 – Efficiency determination according to method 2-1-2A

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7.1.2.2 Test procedure

Couple either the motor under test to a load machine or the generator under test to a motor with a torque meter. Operate the machine under test at the required load.

Record U, I, P_{el}, n, T, cos φ, θ_c.

~~When~~ If excitation is required, proceed according to 5.9.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of permanent magnet motors, physically uncouple the motor under test, to avoid residual torque in unexcited condition induced by permanent magnets. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

7.1.2.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1 + P_{1E}} \tag{72}$$

Input power P_1 and output power P_2 are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$;
– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

where

P_{mech} = 2π × T × n.

P_{1E} is according to 5.9.

NOTE Excitation circuit losses not supplied by P_{1E} are mechanically covered from the shaft.

7.1.3 Method 2-1-2B – Summation of separate losses with a rated load temperature test and a short circuit test

7.1.3.1 General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

– iron losses;
– windage and friction losses;
– stator and rotor copper losses;
– excitation circuit losses;
– additional load losses.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

For an overview, Figure 20 provides a flowchart for efficiency determination by this test method.

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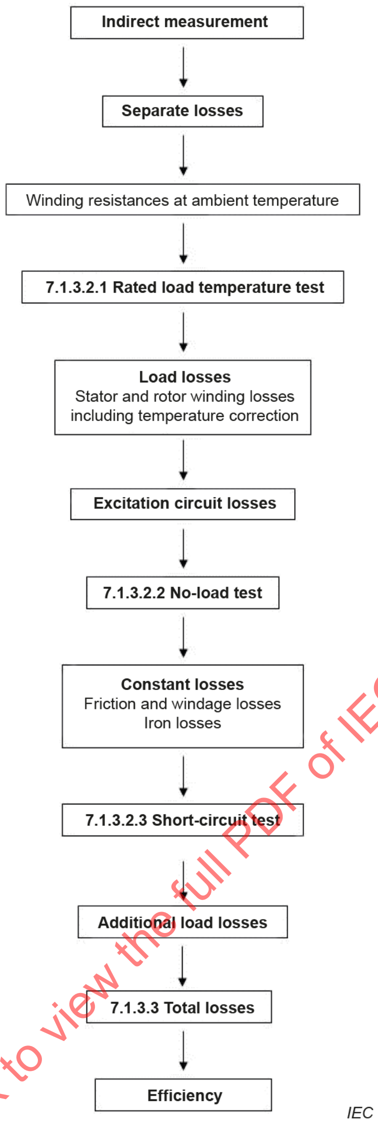

Figure 20 – Efficiency determination according to method 2-1-2B

7.1.3.2 Test procedure

7.1.3.2.1 Rated load temperature test

7.1.3.2.1.1 General

Before this load test, determine the temperature and the winding resistance of the machine with the machine at ambient temperature.

The machine shall be loaded by suitable means, with supply power according to the machine rating and operated until thermal equilibrium is achieved (rate of change of 1 K or less per half hour).

At the end of the rated-load test, record the average of at least 3 sets of test results:

– P_N, I_N, U_N, f, θ_c, θ_N;

– $R_N = R$ (the test resistance for rated load according to 5.7.1);

– θ_N (the winding temperature at rated load according to 5.7.2);

– Excitation system values according to 5.9.

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7.1.3.2.1.2 Stator winding losses

Determine the stator-winding losses:

$$P_s = 1{,}5 \times I^2 \times R_{ll} \tag{73}$$

where

R_{ll} is according to 5.7.1, corrected to 25 °C primary coolant reference temperature.

7.1.3.2.1.3 Field winding loss

The field winding loss is

$$P_f = I_f \cdot U_f \tag{74}$$

7.1.3.2.1.4 Electrical losses in brushes

In case of brushes determine brush losses from an assigned voltage drop per brush of each of the two polarities:

$$P_b = 2 \times U_b \times I_e \tag{75}$$

where

I_e is according to the load test;

U_b is the voltage drop per brush of each of the two polarities depending on brush type:

1,0 V for carbon, electrographitic or graphite;

0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

7.1.3.2.1.5 Exciter loss

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input according to the input-output method; or

b) a calibrated driving motor to measure the motor electrical power input.

Connect the exciter (in the case of a synchronous machine excited via slip-rings) to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for rated load.

Record:

– U_e, I_e, P_{1E}, n, T_E for rated load;

– $T_{E,0}$ (the torque with the exciter unexcited).

The exciter loss is:

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$$P_{Ed} = 2\pi n\left(T_E - T_{E,0}\right) + P_{1E} - P_f \tag{76}$$

When the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The total excitation loss is:

$$P_e = P_f + P_{Ed} + P_b \tag{77}$$

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7.1.3.2.2 No-load test

7.1.3.2.2.1 General

machine can be tested running as an uncoupled motor or coupled with a driving machine and operating as a generator (supplied power from shaft, measured according input-output method).

The no-load test shall be carried out on a hot machine immediately after the rated load test.

When this is not possible the test may also be carried out starting with a cold machine but the no-load losses shall be stabilized at rated frequency and voltage (by adjusting the excitation current), and unity power factor (minimum current) when running as an uncoupled motor.

In the case of a synchronous machine with shaft driven exciter (see 3.13.3.3a)), the machine should be separately excited and the exciter disconnected from its supply and from the excitation winding.

The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at a minimum number of eight values of voltage, including rated voltage, so that:

– four or more values are read approximately equally spaced between approximately 110 % and 80 % of rated voltage;
– four or more values are read approximately equally spaced between approximately 70 % and approximately 30 % of rated voltage, or (for an uncoupled running machine) to a point where the current no longer decreases.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linear with the electrical power P_0.

~~NOTE 1~~ R_0 is $R_{ll,0}$. Where resistance measurement is impracticable due to very low resistances, calculated values are permissible. The calculated values have to be based on the average value of the measured winding temperatures.

For a coupled machine, P_0 is determined from T and n.

Record excitation system values according to 5.9.

~~NOTE 2~~ For large synchronous machines, it is recommended to record other values influencing efficiency, for example coolant temperature, gas purity, gas pressure, sliding bearings oil temperature, bearing oil viscosity.

7.1.3.2.2.2 Constant losses

For each value of voltage determine the constant losses:

$$P_c = P_0 - P_{s0} \tag{78}$$

where

$$P_{s0} = 1{,}5 \cdot I_0^2 \cdot R_{||0} \tag{79}$$

For machines with brushless exciters, excitation losses shall also be subtracted as follows:

$$P_c = P_0 - P_{s0} - P_{f,0} - P_{Ed,0} + P_{1E,0} \tag{80}$$

where

$P_{f,0}$ is the excitation winding losses at no-load;

$P_{Ed,0}$ is the exciter loss (see above) corresponding to U_e and I_e of the test point;

$P_{1E,0}$ is the power according to 5.9 corresponding to U_e and I_e of the test point.

7.1.3.2.2.3 Friction and windage losses

From the no-load test points, use all that show no significant saturation effect and develop a curve of constant losses (P_c), against the voltage squared (U_0^2). Extrapolate a straight line to zero voltage. The intercept with the zero voltage axis is the friction and windage losses P_{fw}.

~~NOTE 3~~ Windage and friction losses are considered to be independent of load and the same windage and friction loss values may be used for each of the load points.

7.1.3.2.2.4 Iron losses

For each of the values of voltage develop a curve of constant losses against voltage. Subtract from this value the windage and friction losses to determine the iron losses.

$$P_{fe} = P_c - P_{fw} \tag{81}$$

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7.1.3.2.3 Short-circuit test

7.1.3.2.3.1 Short-circuit test with coupled machine

Couple the machine under test with its armature winding short-circuited to a drive machine, with provisions to record the torque using a torque meter ~~or dynamometer~~ (see method 2-1-2A). Operate at rated speed and excited so that the current in the short-circuited primary winding is equal to the rated current.

In the case of a machine with a shaft driven exciter (see 3.13.3.3a)), the machine should be separately excited and the exciter disconnected from its supply and from the excitation winding.

The sum of the load losses and the additional load losses is assumed to be temperature independent, and no correction to a reference temperature is made. It is assumed that the additional load losses vary as the square of the stator current.

Record: T, n, I.

Excitation system values are according to 5.9.

7.1.3.2.3.2 Short-circuit test with uncoupled machine

7.1.3.2.3.2.1 General

The machine is operated as a synchronous motor at a fixed voltage, preferably about 1/3 normal or at the lowest value for which stable operation can be obtained. The armature current is varied by control of the field current. The armature current should be varied in about six steps between 125 % and 25 % of rated current and should include one or two points at very low current. The maximum test current value, traditionally set at 125 %, should be obtained from the manufacturer since sometimes stator cooling will not permit operation in excess of 100 % rated current without damage. The highest readings should be taken first to secure more uniform stator winding temperatures during the test.

Record: P_1, I, U.

Excitation system values are according to 5.9.

NOTE For large machines, the maximum step may be limited to 60 % to 70 % of rated armature current.

7.1.3.2.3.2.2 Additional load losses

7.1.3.2.3.2.2.1 From test with coupled machine

The additional load losses at rated current result from the absorbed power of the short-circuit test with coupled machine diminished by the friction and windage losses P_{fw} and the load loss at rated current.

$$P_{LL,N} = 2\pi nT - P_{fw} - P_s \qquad (82)$$

In the case of a machine with brushless excitation, the excitation winding and the exciter loss part supplied by the driving machine shall additionally be subtracted:

$$P_{LL,N} = 2\pi nT + P_{1E} - P_{fw} - P_s - P_f - P_{Ed} \qquad (83)$$

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For other load points the additional load losses result from

$$P_{LL} = P_{LL,N} \times \left(\frac{I}{I_N}\right)^2 \qquad (84)$$

7.1.3.2.3.2.2.2 From test with uncoupled machine

In order to determine additional load losses at any armature current, the constant losses P_c and the armature winding loss P_s at any armature current shall be subtracted from the power input at each armature current taken in the test.

7.1.3.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \qquad (85)$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1 Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses P_T including excitation circuit losses are:

$$P_T = P_c + P_S + P_{LL} + P_e \qquad (86)$$

7.1.4 Method 2-1-2C – Summation of separate losses without a full load test

Method 2-1-2C shall be applied to machines with ratings above 2 MW. The test procedure is in principle similar to method 2-1-2B. The only difference is that the rated load temperature test is replaced by the determination of the field current by the ASA-, Swedish- or Potier-Diagram (see IEC 60034-4-1).

Apart from that the procedures for loss and efficiency determination are equivalent to method 2-1-2B.

For an overview, Figure 21 provides a flowchart for efficiency determination by this test method.

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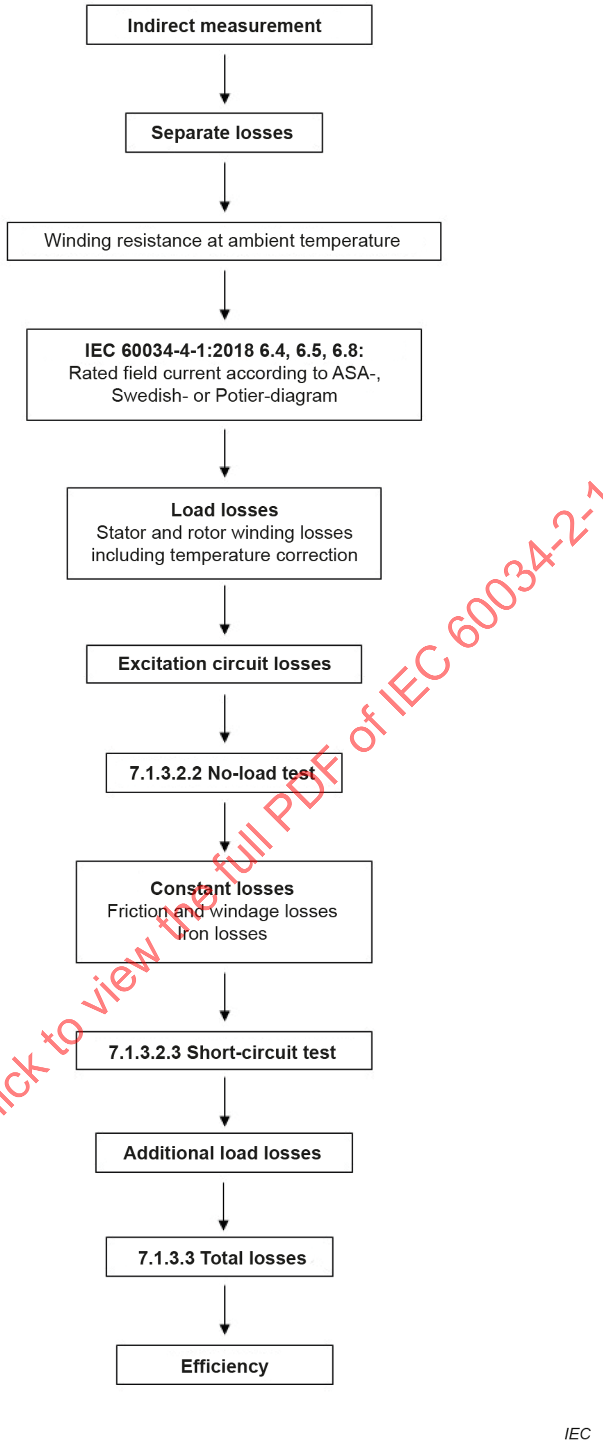

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Figure 21 – Efficiency determination according to method 2-1-2C

Prior to this test, the results of a no-load saturation test, a sustained polyphase short-circuit test and an over-excitation test at zero power factor, in accordance with 6.4, 6.5 and 6.8 of ~~IEC 60034-4:2008~~ IEC 60034-4-1:2018, shall be available.

For the procedures to determine efficiency see 7.1.3, method 2-1-2B.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

7.2 Testing methods for field or routine testing

7.2.1 General

These test methods may be used for any test, i.e. field tests, customer-specific acceptance tests or routine tests.

In addition, preferred methods of Table 4 and Table 5 may also be used outside the power range identified in Table 4 and Table 5

Methods defined by this document are given in Table 6.

Table 6 – Synchronous machines: other methods

Reference	Method	Description	Subclause	Required facility
2-1-2D	Dual-supply-back-to-back	Dual-supply, back-to-back test	7.2.2	Two identical units
2-1-2E	Single-supply-back-to-back test	Single supply, back-to-back test	7.2.3	Two identical units
2-1-2F	Zero power factor with excitation current from Potier / ASA / Swedish diagram	Excitation current from Potier / ASA / Swedish diagram;	7.2.4	Supply for full voltage and current
2-1-2G	Summation of losses with load test except P_{LL}	Without consideration of P_{LL}	7.2.5	Machine set for full load

7.2.2 Method 2-1-2D – Dual supply back-to-back-test

7.2.2.1 General

For an overview, Figure 22 provides a flowchart for efficiency determination by this test method.

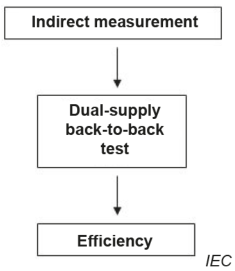

Figure 22 – Efficiency determination according to method 2-1-2D

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

7.2.2.2 Test procedure

Mechanically, couple two identical machines together (see Figure 23). Tests are made with the power supplies exchanged but with the instruments and instrument transformers remaining with the same machine.

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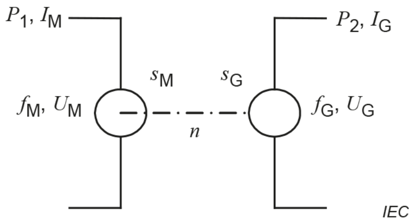

Figure 23 – Sketch for dual supply back-to-back test
($I_M = I_G$, $f_M = f_G$)

The voltage and current of the two machines shall be identical, and one machine (the motor for motor rating, the generator for generator rating) shall have the rated power factor. This can be achieved by a set of synchronous and DC machines feeding the generator output back to the line.

NOTE Power factor and excitation current of the other machine will deviate from rated values because of the losses absorbed by the two machines.

Reverse the motor and generator connections and repeat the test.

For each test, record: U, I, f, P_1, P_2, cos φ_M, cos φ_G, θ_c.

For excitation systems proceed according to 5.9.

7.2.2.3 Efficiency determination

~~When~~ If identical machines are run at essentially the same rated conditions, the efficiency shall be calculated from half the total losses and the average of motor input power ~~of the motor~~ and generator output power as follows:

$$\eta = 1 - \frac{P_T}{\frac{P_1 + P_2}{2} + P_{1E}} \quad (87)$$

where

$$P_T = \frac{1}{2}(P_1 - P_2) + P_{1E}\ ;\ P_{1E} = \frac{1}{2}\left(P_{1E,M} + P_{1E,G}\right) \quad (88)$$

P_{1E} is according to 5.9.

7.2.3 Method 2-1-2E – Single supply back-to-back-test

7.2.3.1 General

For an overview, Figure 24 provides a flowchart for efficiency determination by this test method.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

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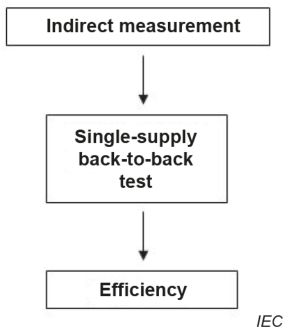

Figure 24 – Efficiency determination according to method 2-1-2E

7.2.3.2 Test procedure

Mechanically couple two identical machines together and connect them both electrically to the same power supply to operate at rated speed and rated voltage, one as a motor and the other as a generator.

NOTE Alternatively, the losses can be supplied by a calibrated driving motor.

Mechanically couple the machines with an angular displacement of their rotors enabling one machine to operate at the load conditions for which the efficiency is required, and the other machine to operate at the same absolute value of stator current (see Figure 25).

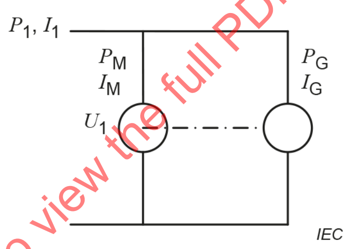

Figure 25 – Single supply back-to-back test for synchronous machines

The displacement expressed as electrical angle α for this condition is approximately the double internal electrical angle at the required load condition. In general, for a given voltage the circulating power depends on the angle α and on the excitation currents of the motor and generator. Adjust the current and power factor to rated values at one machine; the deviation in excitation current from the rated value at the other machine can be used for accuracy considerations.

For each test, record:

– U_1, I_1, P_1 of the power-frequency supply;

– I_M, P_M of the motor;

– I_G, P_G of the generator;

– excitation system values according to 5.9.

7.2.3.3 Efficiency determination

~~When~~ If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

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Calculate the efficiency from

$$\eta = 1 - \frac{P_\mathrm{T}}{P_\mathrm{M} + P_\mathrm{1E}} \tag{89}$$

where

P_M is the power absorbed at the terminals of the machine acting as a motor (excluding excitation power);

P_T is the total losses, defined as half the total absorbed;

P_1E is the excitation power supplied by a separate source.

$$P_\mathrm{T} = \frac{1}{2} P_1 + P_\mathrm{1E}; \quad P_\mathrm{1E} = \frac{1}{2}\left(P_\mathrm{1E,M} + P_\mathrm{1E,G}\right)$$

7.2.4 Method 2-1-2F – Zero power factor test with excitation current from Potier-, ASA- or Swedish-diagram

7.2.4.1 General

For an overview, Figure 26 provides a flowchart for efficiency determination by this test method.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

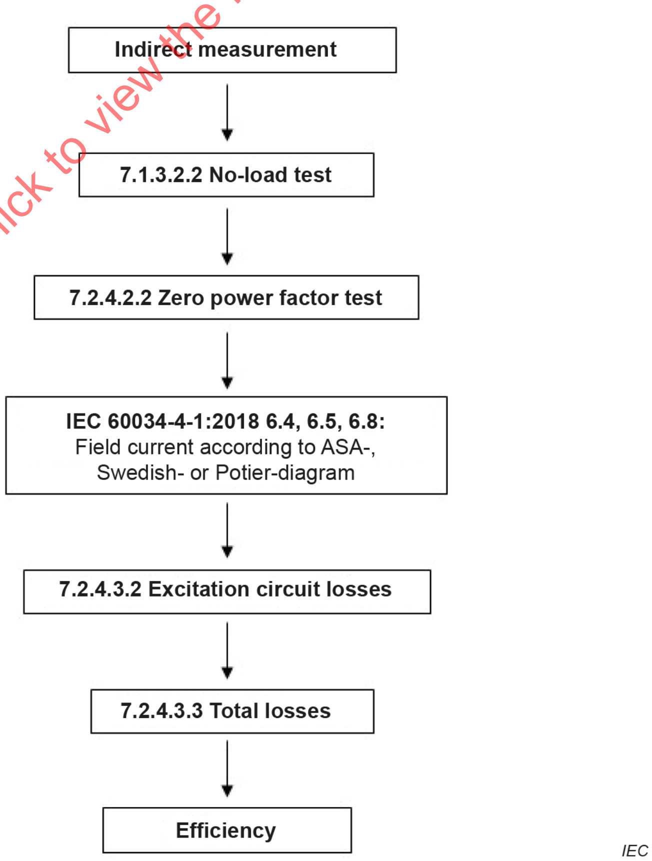

Figure 26 – Efficiency determination according to method 2-1-2F

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7.2.4.2 Test procedure

7.2.4.2.1 General

Prior to this test, the results of a no-load saturation test, a sustained polyphase short-circuit test and an over-excitation test at zero power factor, in accordance with 6.4, 6.5 and ~~6.8 of IEC 60034-4:2008~~ 6.7 of IEC 60034-4-1:2018, shall be available.

The evaluation of the results of the no-load test shall be in accordance with 7.1.3.2.2.

7.2.4.2.2 Zero power factor test

Operate the machine uncoupled as a motor, at rated speed and over-excited. Adjust the supply voltage to the same electromotive force E and armature current I (at a power factor near zero) as at the desired load.

NOTE 1 E is the vectorial sum of terminal voltage and Potier reactance voltage drop according to 7.26.2 of ~~IEC 60034-4:2008~~ IEC 60034-4-1:2018.

The test shall be made as near as possible to the stabilized operating temperature attained in operation at rated load. No winding temperature correction shall be made.

For the above test, it is necessary that the supply voltage is adjustable so that the iron losses have the same value during this test as at a rated power factor under load at rated voltage. If the supply voltage is not adjustable but is equal to the rated voltage, this could give an active iron loss appreciably different from that at full-load. In principle, reactive power should be delivered (i.e. machine over-excited), but when this is impossible due to limited exciter voltage, the test may be made with reactive power absorbed (i.e. machine under-excited) as far as stable running is possible.

The excitation winding losses at the desired load will be obtained from the excitation current estimated according to 7.26.2 of ~~IEC 60034-4:2008~~ IEC 60034-4-1:2018 (Potier diagram), or 7.26.3 (ASA diagram), or 7.26.4 (Swedish diagram).

NOTE 2 The accuracy of this method depends on the accuracy of the wattmeters and the instrument transformers at low power factor.

Record at zero power factor:

– U, f, I, $P_{1,\text{zpf}}$;
– excitation system values according to 5.9;
– θ_c and θ_w.

7.2.4.3 Efficiency determination

7.2.4.3.1 General

For each desired load point, determine the efficiency with the measured values as follows:

$$\eta = 1 - \frac{P_T}{P_1 + P_{1E}} \tag{90}$$

where

$P_1 = \sqrt{3} \times U_N \times I \cos\varphi_N$ is the power absorbed at the armature winding terminals in rated operation;

P_T is the total losses, including excitation losses;

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P_{1E} is the excitation power supplied by a separate source.

7.2.4.3.2 Excitation losses

7.2.4.3.2.1 Field winding loss

The field winding loss is

$$P_f = I_e \cdot U_f = I_e^2 \cdot R_e \tag{91}$$

applying the following temperature correction for the excitation winding resistance:

$$R_e = R_{e,0} \times \frac{235 + \theta_e}{235 + \theta_0}; \quad \theta_e = 25 + (\theta_w - \theta_c)\left(\frac{I_e}{I_{e,zpf}}\right)^2 \tag{92}$$

where

I_e is the excitation winding current determined as described in IEC 60034-4-1;

R_e is the excitation winding resistance, temperature corrected for the desired load;

$R_{e,0}$ is the cold winding resistance at temperature θ_0;

$I_{e,zpf}$ is the excitation winding current from the zero power factor test;

θ_w is the excitation winding temperature of the zpf-test;

θ_c is the reference coolant temperature of the zpf-test;

θ_e is the excitation winding temperature corrected to I_e.

7.2.4.3.2.2 Electrical losses in brushes

In case of brushes determine brush losses from an assigned voltage drop per brush of each of the two polarities:

$$P_b = 2 \times U_b \times I_e \tag{93}$$

where

I_e is the excitation winding current determined as described in IEC 60034-4-1;

U_b is the voltage drop per brush of each of the two polarities depending on brush type:

1,0 V for carbon, electrographitic or graphite;

0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

7.2.4.3.2.3 Exciter loss

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input according to the input-output method; or

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b) a calibrated driving motor to measure the motor electrical power input.

Connect the exciter (in the case of a synchronous machine excited via slip-rings) to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for rated load.

Record:

– U_e, I_e, P_{1E}, n, T_E for rated load;

– $T_{E,0}$ (the torque with the exciter unexcited).

The exciter loss is:

$$P_{Ed} = 2\pi n\left(T_E - T_{E,0}\right) + P_{1E} - P_f \quad (94)$$

~~When~~ If the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The total excitation loss is:

$$P_e = P_f + P_{Ed} + P_b \quad (95)$$

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7.2.4.3.3 Total losses

For machines with exciter types c) and d) (see 3.13.3.3) the total losses are:

$$P_T = P_{1,zpf} + \Delta P_{fe} + P_e \quad (96)$$

where

$P_{1,zpf}$ is the absorbed power at zero power factor test;

Δp_{fe} is determined from the iron loss-voltage curve (see 7.1.3.2.2), and is the difference of the values at voltages equal to the e.m.f. for the desired load and the e.m.f. of the zero power factor test;

P_e determined as stated above.

For machines with exciters type a) and b) (see 3.13.3.3) the total losses are:

P_e, P_{ed} and P_{1E} are as defined above for the excitation winding current of the desired load, determined according to IEC 60034-4-1:

$$P_T = P_{1,zpf} + P_{1E,zpf} + \Delta P_{fe} + P_e \quad (97)$$

$$P_e = P_f + P_{Ed} - P_{f,zpf} - P_{Ed,zpf} \quad (98)$$

where

$P_{1,zpf}$, $P_{f,zpf}$ and $P_{1E,zpf}$	are measured values from the zero power factor test;
P_f	is determined as for separately excited machines;
P_{Ed}, $P_{Ed,zpf}$	are determined from a test as stated above for I_e, R_e and $I_{e,zpf}$, $R_{e,zpf}$;
ΔP_{fe}	is determined from the iron loss-voltage curve (see 7.1.3.2.2), and is the difference of the values at voltages equal to the e.m.f. for the desired load and the e.m.f. of the zero power factor test.

NOTE The formulas are expressed for motor operation.

7.2.5 Method 2-1-2G – Summation of separate losses with a load test without consideration of additional load losses

The test procedure is in principle similar to method 2-1-2B. The only difference is that the additional load losses are not considered by this method, i.e. the short circuit test for their determination is skipped. This results in a significantly lower accuracy.

Apart from that, the procedures for loss and efficiency determination are equivalent to method 2-1-2B.

For an overview, Figure 27 provides a flowchart for efficiency determination by this test method.

For the procedures to determine efficiency see 7.1.3, method 2-1-2B, without consideration of the additional load loss.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

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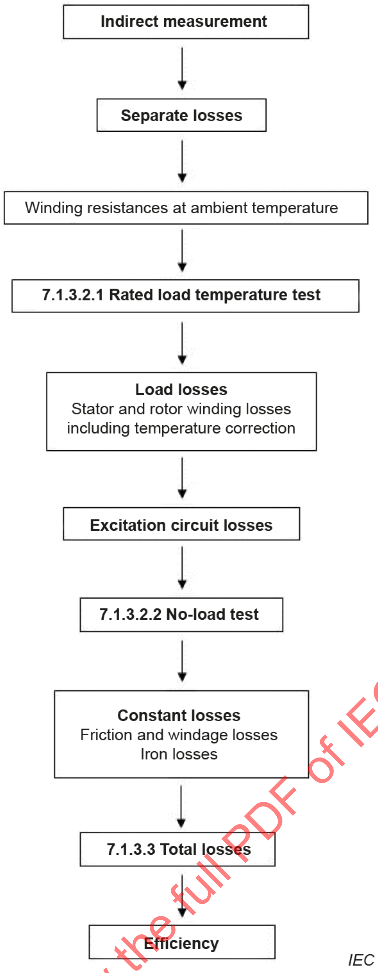

Figure 27 – Efficiency determination according to method 2-1-2G

8 Test methods for the determination of the efficiency of DC machines

8.1 Testing methods for field or routine testing

~~8.1.1 General~~

The methods shall be used for field tests, customer specific acceptance tests or routine tests.

Methods defined by this document are given in Table 7.

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Table 7 – DC machines: test methods

Reference	Method	Description	Subclause	Required facility
2-1-3A	Direct measurement: Input-output	Torque measurement	8.2	~~Dynamometer~~ Torque measuring device for full-load
2-1-3B	Summation of losses with load test and DC component of additional load losses from test	P_{LL} DC component from single supply back-to-back test	8.3	Two identical units, booster generator, specified rectifier
2-1-3C	Summation of losses with load test and DC component of additional load losses from assigned value	P_{LL} DC component from assigned value	8.4	Specified rectifier
2-1-3D	Summation of losses without a load test	Excitation loss from an assigned ratio of load to no-load excitation current P_{LL} from assigned value	8.5	
2-1-3E	Single-supply-back-to-back test	Single supply, back-to-back test	8.6	Two identical units Booster generator

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8.2 Method 2-1-3A – Direct measurement of input and output

8.2.1 General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the armature is measured in the same test.

Input and output power are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 28);

– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

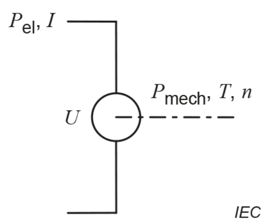
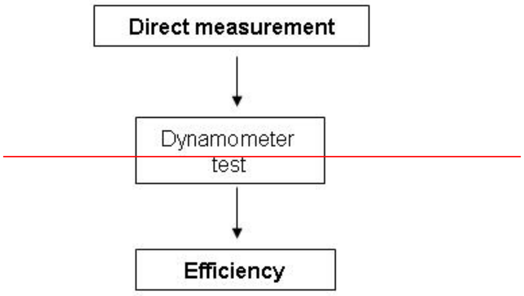


Figure 28 – Sketch for torque measurement test

For an overview, Figure 29 provides a flowchart for efficiency determination by this test method.



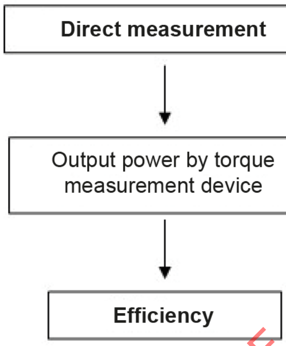


Figure 29 – Efficiency determination according to method 2-1-3A

8.2.2 Test procedure

Couple either the motor under test to a load machine or the generator under test to a motor with a torque meter. Operate the machine under test at the required load.

Record U, I, P_{el}, n, T, θ_c.

~~When~~ If excitation is required, proceed according to 5.9.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

8.2.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1 + P_{1E}} \tag{99}$$

Input power P_1 and output power P_2 are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$;

– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$;

where

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P_{mech} = $2\pi \times T \times n$;

P_{1E} is according to 5.9.

NOTE Excitation circuit losses not supplied by P_{1E} are mechanically covered from the shaft.

8.3 Method 2-1-3B – Summation of losses with a load test and DC component of additional load losses from test

8.3.1 General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

- iron losses;
- windage and friction losses;
- armature winding and brush losses;
- excitation circuit and exciter losses;
- additional load losses.

For an overview, Figure 30 provides a flowchart for efficiency determination by this test method.

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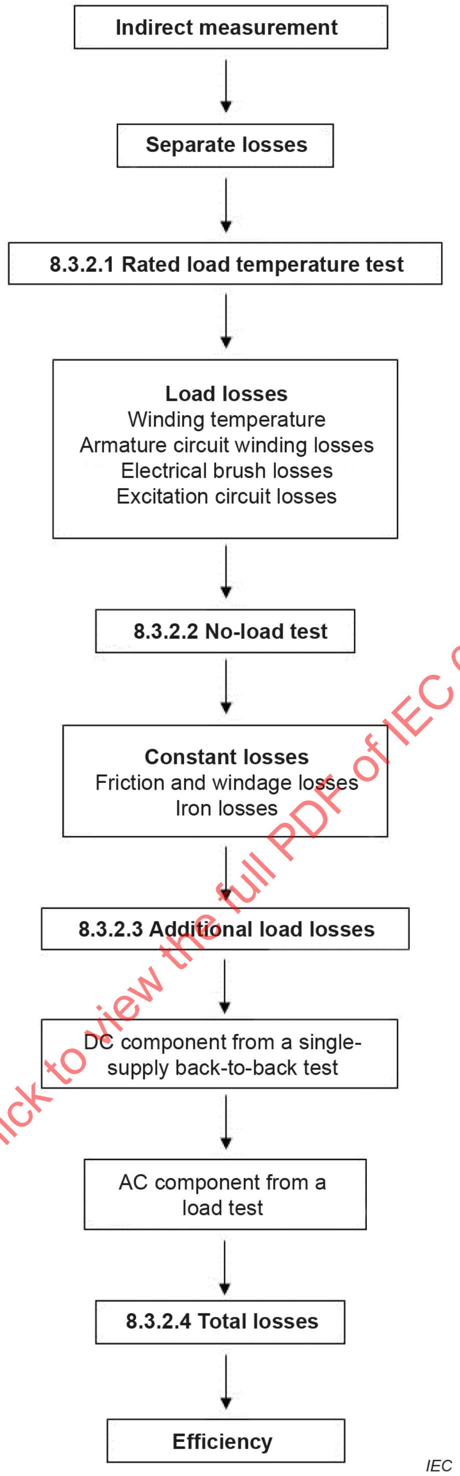

Figure 30 – Efficiency determination according to method 2-1-3B

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8.3.2 Test procedure

8.3.2.1 Rated load temperature test

8.3.2.1.1 General

Before this load test, determine the ambient temperature and the winding resistance of the motor.

The machine shall be loaded by suitable means, with supply power according to the machine rating and operated until thermal equilibrium is achieved (rate of change of 1 K or less per half hour).

At the end of the rated-load test, record the average of at least 3 sets of test results:

– P_N, I_N, U_N, θ_c, θ_N;
– $R_N = R$ (the test resistance for rated load according to 5.7.1);
– θ_N (the winding temperature at rated load according to 5.7.2);
– excitation system values according to 5.9.

In the case of DC machines on rectified power, the mean value I_{av} and the RMS value I shall be measured.

For DC machines, R is the total resistance of all windings carrying armature current (armature, commutating, compensating winding, compound winding). Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

8.3.2.1.2 Armature circuit winding losses

For each load recorded determine the armature-circuit-windings losses:

$$P_a = I^2 \times R \tag{100}$$

R according to 5.7.2 with R taking all windings in the armature circuit into account.

8.3.2.1.3 Electrical brush losses

Determine brush losses using an assigned voltage drop per brush:

$$P_b = 2 \times U_b \times I \tag{101}$$

where

I is the armature current at the rating considered;

U_b is the assumed voltage drop per brush depending on brush type:

1,0 V for carbon, electrographitic or graphite;

0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

8.3.2.1.4 Excitation circuit losses

The excitation winding losses result from the measured voltage and current as follows:

$$P_f = U_e \times I_e \tag{102}$$

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8.3.2.1.5 Exciter losses

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input;

b) a calibrated driving motor to measure the motor electrical power input.

Connect the exciter to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for each of the load points.

Record:

– U_e, I_e, P_{Ed}, n, T_E for each load point (P_{Ed} according to 3.13.3.3);

– $T_{E,0}$ (the torque with the exciter unexcited).

~~When~~ If the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The exciter losses P_{Ed} are

$$P_{Ed} = \left(T_E - T_{E,0}\right) \times 2\pi n + P_{1E} - U_e \times I_e \quad (103)$$

where $T_{E,0}$ is the torque with the exciter unexcited.

If testing is not practical, calculated losses shall be used.

8.3.2.2 No-load test

8.3.2.2.1 General

The machine can be tested running as an uncoupled motor or coupled with a driving machine and operating as a generator (supplied power from torque, measured according input-output method).

The no-load test shall be carried out on a hot machine immediately after the rated load test.

~~When~~ If this is not possible the test may also be carried out starting with a cold machine but the no-load losses shall be stabilized. The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at a minimum number of eight values of voltage, including rated voltage, so that:

– four or more values are read approximately equally spaced between 110 % and 80 % of rated voltage;

– four or more values are read approximately equally spaced between 70 % and approximately 30 % of rated voltage, or (for an uncoupled running machine) to a point where the current no longer decreases.

For uncoupled DC machines, the speed shall be maintained constant by adjusting the field current.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

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Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linear with the electrical power P_0.

Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

For a coupled machine, P_0 is determined from T and n.

8.3.2.2.2 Constant losses

Determine the constant losses from the following formula:

$$P_c = P_0 - P_a \tag{104}$$

where

$$P_a = I_0^2 \times R_0 \tag{105}$$

I_0 and R_0 are recorded for each value of voltage.

~~When~~ If resistance measurement is impracticable due to very low resistances, calculated values are permissible, corrected to the expected winding temperature.

NOTE In the armature losses P_a, the following are included: compensating windings, commutating pole windings and shunt resistors (diverters). In the case of diverters in parallel with a series winding, the electrical winding losses may be determined using the total current and the resulting resistance.

8.3.2.2.3 Friction and windage losses (optional)

For each of the values of voltage 70 % or less develop a curve of constant losses (P_c) against voltage U_0^2. Extrapolate a straight line to zero voltage. The intercept with the zero voltage axis is the windage and friction losses P_{fw}.

8.3.2.2.4 Iron losses (optional)

For each of the values of voltage between 80 % and 110 % develop a curve of constant losses (P_c) against voltage U_0. The iron loss shall be taken for the inner voltage U_i, at:

$$U_i = U_N - (IR)_a - 2U_b \text{ in the case of a motor} \tag{106}$$

$$U_i = U_N + (IR)_a + 2U_b \text{ in the case of a generator} \tag{107}$$

where

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U_N is the rated voltage;

$2U_b$ is the brush voltage-drop as given at the load test;

I is the current of the desired load point;

R is the resistance of all windings of the armature circuit at full-load temperature.

Determine the iron loss from

$$P_{fe} = P_c - P_{fw} \quad (108)$$

8.3.2.3 Additional load losses

8.3.2.3.1 DC losses from single supply back-to-back-test

This method allows the determination of the DC component of the additional load losses ~~when~~ if two identical DC machines are available. They shall be coupled and electrically connected together and supplied by a DC source, the machine acting as a generator with a booster generator in series (see Figure 31).

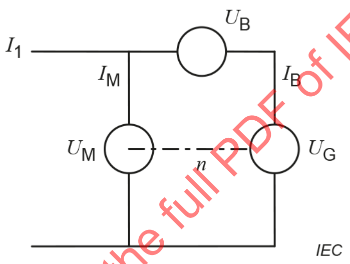

Figure 31 – Sketch for single supply back-to-back test for determination of DC component of additional load losses

If the machines are designed for motor operation, the supply shall deliver rated voltage and rated current to the machine acting as motor. In the case of machines designed for generator operation, the supply voltage shall be adjusted to rated voltage and rated current at the machine acting as generator. The motor and the generator shall be operated with the flux required to produce the e.m.f. corresponding to the test load.

NOTE The voltage supply mainly covers the no-load losses, the booster mainly covers the load losses.

In the case of machines with shaft driven exciters, the excitation windings shall be separately excited for this test, with the exciters disconnected from their supply and the excitation winding.

When temperatures have stabilized, record: U, I, U_B, I_B, $U_{e,M}$, $I_{e,M}$, $U_{e,G}$, $I_{e,G}$, n, θ_c.

The DC component of the additional load loss is

$$P_{LL} = \frac{1}{2}\left(P_1 - \sum P_c - \sum P_a - P_{con} - 2U_b(I + I_B) - 2I_B U_b\right) \quad (109)$$

where

$P_1 = U_M \times I_1 + U_B \times I_B$ is the power from supply and booster; see Figure 31;

ΣP_c is the sum of constant losses of both machines;

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ΣP_a is the sum of the resistance losses of both armature circuits;

P_{con} is the loss in cable connections.

For determination of losses for other load points, apply the factors as described in Table 8.

8.3.2.3.2 AC losses (converter-fed DC machines)

For motors supplied by static power converters, whenever the current ripple factor (see IEC 60034-1) of the armature current exceeds 0,1, the additional losses caused by the AC component of the armature current shall be considered in addition to the losses specified above.

The losses are obtained from a load test with the machine supplied by an appropriate rectifier. See also IEC 60034-19.

Record:

– P_1 the AC power supplied to the machine;

– I the AC r.m.s. current component; and

– θ_w the temperatures of the windings in galvanic contact with the armature circuit.

NOTE For series-wound motors, a small amount of the AC power input contributes to the developed motor torque. This amount is usually so small that it can be neglected.

The additional losses due to the AC part of the supply voltage result from:

$$P_{LL} = P_1 - I^2 \times R \tag{110}$$

where R is the DC resistance of the armature circuit at rated load temperatures according to 5.7.2.

8.3.2.4 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \tag{111}$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1 Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

~~Total losses~~

The total losses shall be taken as the sum of the separate losses consisting of

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$$P_T = P_c + P_a + P_b + P_{LL} + P_e \quad (112)$$

$$P_e = P_f + P_{Ed} \quad (113)$$

where

P_a is the armature-winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional load losses;

P_f is the excitation (field winding) loss;

P_{Ed} is the exciter loss.

8.4 Method 2-1-3C – Summation of losses with a load test and DC component of additional load losses from assigned value

8.4.1 General

As method 2-1-3B, this test method determines efficiency by the summation of separate losses. But in this case the DC component of the additional load losses is derived from an assigned value.

For an overview, Figure 32 provides a flowchart for efficiency determination by this test method.

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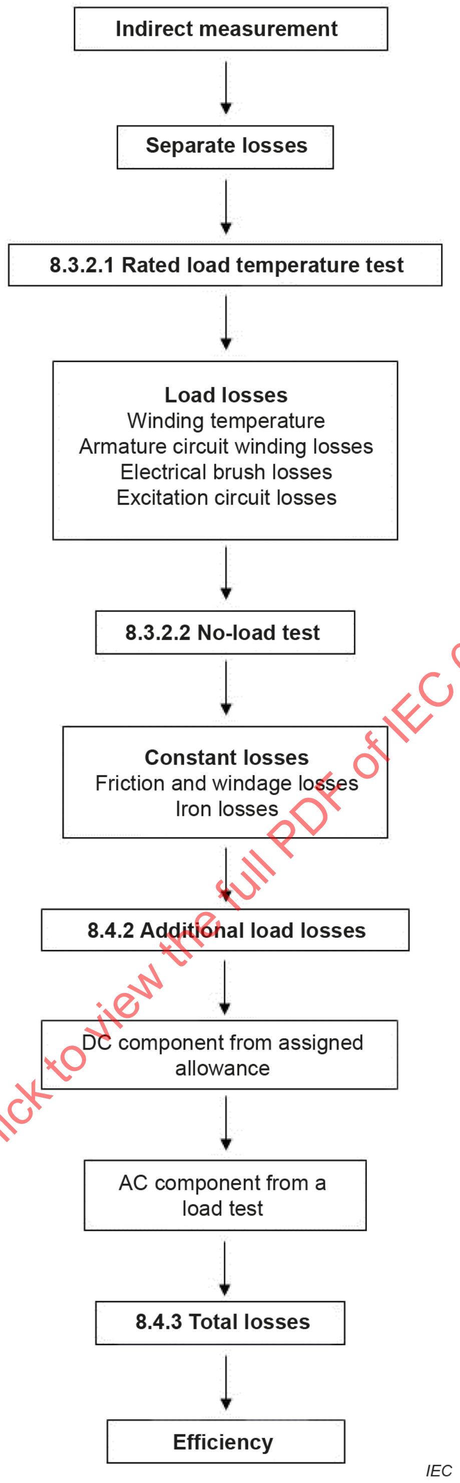

Figure 32 – Efficiency determination according to method 2-1-3C

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8.4.2 Test procedure

8.4.2.1 General

Apart from the determination of the DC component of the additional load losses, the same procedures as in 8.3.2 shall be applied.

8.4.2.2 DC component of the additional load losses from assigned allowance

It is assumed that the DC losses vary as the square of the current, and that their total value at maximum rated current is:

a) for uncompensated machines:
   – 1 % of the rated input power for motors;
   – 1 % of the rated output power for generators;

b) for compensated machines:
   – 0,5 % of the rated input power for motors;
   – 0,5 % of the rated output power for generators.

For constant speed machines, the rated power is the power with maximum rated current and maximum rated voltage.

For variable speed motors where the speed change is obtained by applied voltage, the rated input power is defined at each speed as being the input power when the maximum rated current is associated with the applied voltage of the particular speed considered.

For variable speed motors where the increase in speed is obtained by weakening the field, the rated input power is defined as being the input power when the rated voltage is associated with the maximum rated current. For variable speed generators where the voltage is maintained constant by varying the field, the rated output power is defined as being the output power, which is available at the terminals at rated voltage and maximum rated current. The allowances for additional losses at the speed corresponding to the full field shall be as specified above under a) and b). The allowances for additional losses at other speeds shall be calculated using the appropriate multiplying factors given in Table 8.

Table 8 – Multiplying factors for different speed ratios

Speed ratio	Factor
1,5:1	1,4
2:1	1,7
3:1	2,5
4:1	3,2

The speed ratio in the first column of Table 8 shall be taken as the ratio of actual speed under consideration to the minimum rated speed for continuous running.

For speed ratios other than those given in Table 8, the appropriate multiplying factors may be obtained by interpolation.

8.4.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \tag{114}$$

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where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1 Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

~~Total losses~~

The total losses shall be taken as the sum of the separate losses consisting of

$$P_T = P_c + P_a + P_b + P_{LL} + P_e \quad (115)$$

$$P_e = P_f + P_{Ed} \quad (116)$$

where

P_a is the armature winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional losses;

P_f is the excitation (field winding) loss;

P_{Ed} is the exciter loss.

8.5 Method 2-1-3D – Summation of losses without a load test

8.5.1 General

As method 2-1-3C, this test method determines efficiency by the summation of separate losses. But in this case, the armature circuit winding losses and the excitation circuit losses are not determined by a load test, but by calculation.

For an overview, Figure 33 provides a flowchart for efficiency determination by this test method.

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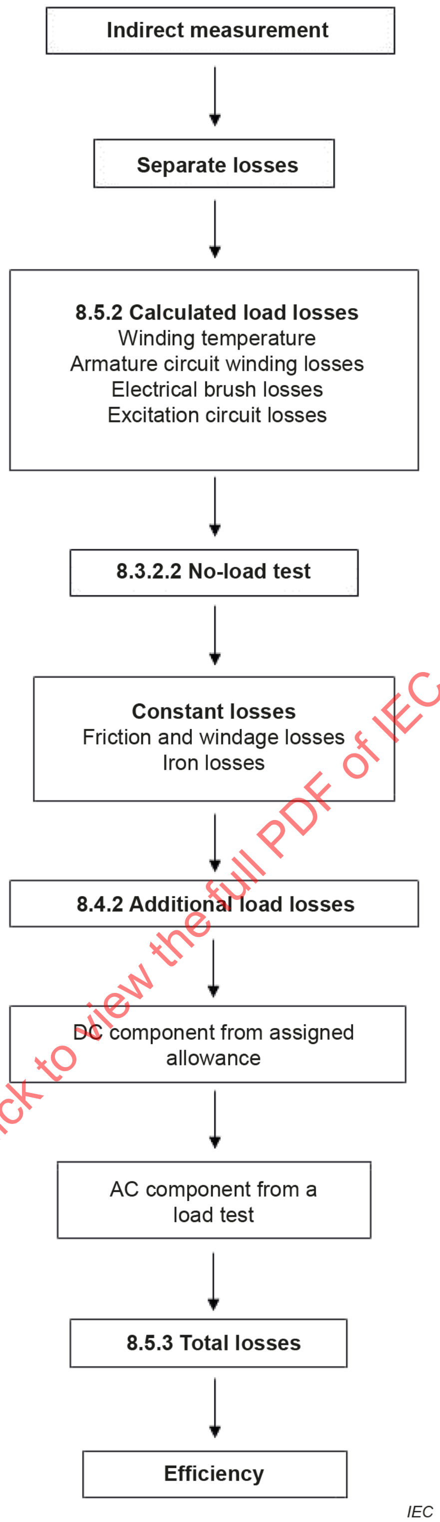

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Figure 33 – Efficiency determination according to method 2-1-3D

8.5.2 Test procedure

8.5.2.1 General

Apart from the determination of the excitation circuit losses, the same procedures as in 8.4.2 shall be applied.

8.5.2.2 Excitation circuit losses

Without a load test, the excitation winding losses P_e shall be calculated from $I_e^2 \times R_f$, where R_f is the resistance of the shunt excitation winding (or separately excited winding), corrected to the reference temperature specified in 5.7.3 and I_e is the excitation current according to the following list.

a) For shunt connected or separately excited generators with or without commutating poles, I_e is 110 % of the excitation current corresponding to no-load at a voltage equal to the rated voltage plus ohmic drop in the armature circuit (armature, brushes and commutating windings if any) at the current of the specific load point.

b) For compensated shunt or separately excited generators, I_e is the excitation current corresponding to no-load at a voltage equal to the rated voltage plus ohmic drop in the armature circuit at the current of the specific load point.

c) For level-compounded generators, I_e is the excitation current for the rated no-load voltage.

d) For over-compounded and under-compounded generators, and special types of generator not covered by items a) to c), I_e is subject to agreement.

e) For shunt wound motors, I_e is equal to no-load excitation current corresponding to the rated voltage.

8.5.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \qquad (117)$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1 Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

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~~**Total losses**~~

The total losses shall be taken as the sum of the separate losses consisting of

$$P_T = P_c + P_a + P_b + P_{LL} + P_e \qquad (118)$$

$$P_e = P_f + P_{Ed} \qquad (119)$$

where

P_a is the armature winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional losses;

P_e is the excitation circuit losses;

P_f is the calculated excitation (field winding) loss;

P_{Ed} is the exciter loss.

8.6 Method 2-1-3E – Single supply back-to-back test

8.6.1 General

For an overview, Figure 34 provides a flowchart for efficiency determination by this test method.

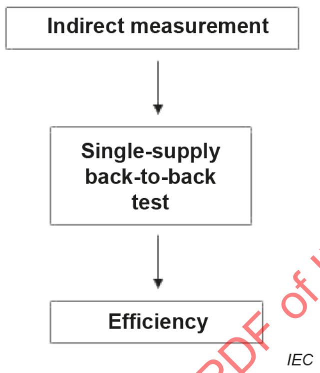

Figure 34 – Efficiency determination according to method 2-1-3E

8.6.2 Test procedure

Mechanically couple two identical machines together and connect them both electrically to the same power supply so as to operate at rated speed and rated voltage, one as a motor and the other as a generator.

NOTE Alternatively, the losses can be supplied either by a calibrated driving motor, a booster, or otherwise by a combination of these various means.

Connect the driven machine to the supply with a booster generator in series (see Figure 35). Operate both machines at approximately the current and the internal voltage corresponding to the load point for which the efficiency is required. For motors, the supply shall deliver rated voltage and the required load to the motor. For generators, the voltage has to be adjusted by the booster for rated voltage and the required load at the generator. The voltage supply mainly covers the no-load losses, the booster covers the load losses.

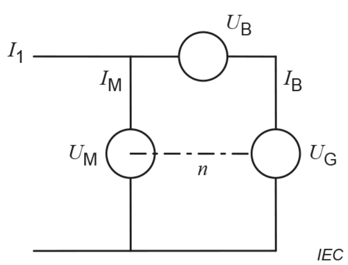

Figure 35 – Sketch for single supply back-to-back test

If no booster is available, the common terminal voltage should be adjusted so that the mean value of the currents of both machines is the rated current.

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For each test, record:

- U_M, I_1 of the power supply;
- P_M absorbed at the motor terminals;
- U_B, I_B of the booster;
- n, θ_c.

For excitation systems, proceed according to 5.9.

8.6.3 Efficiency determination

~~When~~ If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

Calculate the efficiency from

$$\eta = 1 - \frac{P_T}{P_M + P_{1E}} \quad (120)$$

where

P_M is the power absorbed at the terminals of the machine acting as a motor (excluding excitation power);

P_T is the total losses, defined as half the total absorbed;

P_{1E} is the excitation power supplied by a separate source;

$$P_T = \frac{1}{2}\left(U_M \times I_1 + U_B \times I_B\right) + P_{1E} \;; \qquad P_{1E} = \frac{1}{2}\left(P_{1E,M} + P_{1E,G}\right) \quad (121)$$

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Annex A
(normative)

Calculation of values for the Eh-star method

Determine the following complex voltages and currents from the test results:

$$
\begin{aligned}
\underline{U}_{\mathrm{UV}} &= U_{\mathrm{UV}} \\
U'_{\mathrm{WU}} &= \frac{U_{\mathrm{VW}}^2 - U_{\mathrm{WU}}^2 - U_{\mathrm{UV}}^2}{2 \cdot U_{\mathrm{UV}}} \\
U''_{\mathrm{WU}} &= \sqrt{U_{\mathrm{WU}}^2 - U_{\mathrm{WU}}^{'2}} \\
U'_{\mathrm{VW}} &= -U_{\mathrm{UV}} - U'_{\mathrm{WU}} \\
U''_{\mathrm{VW}} &= -U''_{\mathrm{WU}} \\
I'_{\mathrm{V}} &= -\frac{(P_{\mathrm{UV}} - P_{\mathrm{VW}}) + U_{\mathrm{WU}} \cdot I_{\mathrm{W}}}{U_{\mathrm{UV}}}
\end{aligned}
\qquad (A.1)
$$

In the above formula, it is assumed that current I_{W} is in phase with voltage U_{WU}. In the case where the impedance of the resistor contains a noticeable reactive component, use the following formula

$$I'_{\mathrm{V}} = -\frac{(P_{\mathrm{UV}} - P_{\mathrm{VW}}) + R_{\mathrm{eh}} \cdot I_{\mathrm{W}}^2}{U_{\mathrm{UV}}}$$

where R_{eh} is the measured value of the resistive component.

$$
\begin{aligned}
I''_{\mathrm{V}} &= \sqrt{I_{\mathrm{V}}^2 - I_{\mathrm{V}}^{'2}} \\
k_1 &= \frac{1}{2 \cdot I_{\mathrm{V}}^2} \cdot \left(I_{\mathrm{W}}^2 - I_{\mathrm{U}}^2 - I_{\mathrm{V}}^2\right) \\
I'_{\mathrm{U}} &= k_1 \cdot I'_{\mathrm{V}} + \sqrt{\left(k_1^2 - \frac{I_{\mathrm{U}}^2}{I_{\mathrm{V}}^2}\right)\left(I_{\mathrm{V}}^{'2} - I_{\mathrm{V}}^2\right)} \\
I''_{\mathrm{U}} &= \frac{k_1 I_{\mathrm{V}}^2 - I'_{\mathrm{U}} \cdot I'_{\mathrm{V}}}{I''_{\mathrm{V}}} \\
I'_{\mathrm{W}} &= -I'_{\mathrm{U}} - I'_{\mathrm{V}} \\
I''_{\mathrm{W}} &= -I''_{\mathrm{U}} - I''_{\mathrm{V}}
\end{aligned}
\qquad (A.2)
$$

Determine the inner line-to-line voltages from the complex line-to-line voltages and currents:

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$$\underline{U}_{\text{iUV}} = \underline{U}_{\text{UV}} + \frac{R_{\text{VW}}}{2} \cdot \left(\underline{I}_{\text{V}} - \underline{I}_{\text{U}}\right)$$
$$\underline{U}_{\text{iVW}} = \underline{U}_{\text{VW}} + \frac{R_{\text{VW}}}{2} \cdot \left(\underline{I}_{\text{W}} - \underline{I}_{\text{V}}\right) \quad \text{(A.3)}$$
$$\underline{U}_{\text{iWU}} = \underline{U}_{\text{WU}} + \frac{R_{\text{VW}}}{2} \cdot \left(\underline{I}_{\text{U}} - \underline{I}_{\text{W}}\right)$$

Separate into positive and negative sequence line-to-line components ($\underline{a} = e^{j2\pi/3}$):

$$\underline{U}_{\text{iLL(1)}} = \frac{1}{3} \cdot \left(\underline{U}_{\text{iUV}} + \underline{a} \cdot \underline{U}_{\text{iVW}} + \underline{a}^2 \cdot \underline{U}_{\text{iWU}}\right)$$
$$\underline{U}_{\text{iLL(2)}} = \frac{1}{3} \cdot \left(\underline{U}_{\text{iUV}} + \underline{a}^2 \cdot \underline{U}_{\text{iVW}} + \underline{a} \cdot \underline{U}_{\text{iWU}}\right) \quad \text{(A.4)}$$

Determine the positive and negative sequence components of the inner phase voltage $\underline{U}_{\text{i}}$:

$$\underline{U}_{\text{i(1)}} = \frac{1}{\sqrt{3}} \cdot e^{-j\frac{\pi}{6}} \cdot \underline{U}_{\text{iLL(1)}}$$
$$\underline{U}_{\text{i(2)}} = \frac{1}{\sqrt{3}} \cdot e^{j\frac{\pi}{6}} \cdot \underline{U}_{\text{iLL(2)}} \quad \text{(A.5)}$$

Determine the asymmetrical inner phase voltages:

$$\underline{U}_{\text{iU}} = \underline{U}_{\text{i(1)}} + \underline{U}_{\text{i(2)}}$$
$$\underline{U}_{\text{iV}} = \underline{a}^2 \cdot \underline{U}_{\text{i(1)}} + \underline{a} \cdot \underline{U}_{\text{i(2)}} \quad \text{(A.6)}$$
$$\underline{U}_{\text{iW}} = \underline{a} \cdot \underline{U}_{\text{i(1)}} + \underline{a}^2 \cdot \underline{U}_{\text{i(2)}}$$

Determine the iron loss resistance:

$$R_{\text{fe}} = \frac{U_{\text{t}}^2}{P_{\text{fe}}} \quad \text{(A.7)}$$

where

U_{t} is according to 6.2.5.2;

P_{fe} is according to 6.1.3.2.5.

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$$\underline{I}_{\mathrm{feU}} = \frac{\underline{U}_{\mathrm{iU}}}{R_{\mathrm{fe}}} \qquad \underline{I}_{\mathrm{feV}} = \frac{\underline{U}_{\mathrm{iV}}}{R_{\mathrm{fe}}} \qquad \underline{I}_{\mathrm{feW}} = \frac{\underline{U}_{\mathrm{iW}}}{R_{\mathrm{fe}}} \tag{A.8}$$

Determine the inner phase currents:

$$\underline{I}_{\mathrm{iU}} = \underline{I}_{\mathrm{U}} - \underline{I}_{\mathrm{feU}} \qquad \underline{I}_{\mathrm{iV}} = \underline{I}_{\mathrm{V}} - \underline{I}_{\mathrm{feV}} \qquad \underline{I}_{\mathrm{iW}} = \underline{I}_{\mathrm{W}} - \underline{I}_{\mathrm{feW}} \tag{A.9}$$

Determine the positive and negative sequence components of the inner phase currents:

$$\underline{I}_{\mathrm{i(1)}} = \frac{1}{3} \cdot \left(\underline{I}_{\mathrm{iU}} + \underline{a} \cdot \underline{I}_{\mathrm{iV}} + \underline{a}^2 \cdot \underline{I}_{\mathrm{iW}} \right) \qquad \underline{I}_{\mathrm{i(2)}} = \frac{1}{3} \cdot \left(\underline{I}_{\mathrm{iU}} + \underline{a}^2 \cdot \underline{I}_{\mathrm{iV}} + \underline{a} \cdot \underline{I}_{\mathrm{iW}} \right) \tag{A.10}$$

The absolute values of the positive sequence current $I_{\mathrm{i(1)}}$ shall be less than 30 % of the absolute value of the negative sequence current $I_{\mathrm{i(2)}}$ in order to achieve accurate results. If this condition is not met, the test shall be repeated using a different value of R_{eh}.

Determine the air-gap power:

$$P_{\delta(1)} = 3 \cdot \left(U'_{i(1)} \cdot I'_{i(1)} + U''_{i(1)} \cdot I''_{i(1)} \right) \qquad P_{\delta(2)} = 3 \cdot \left(U'_{i(2)} \cdot I'_{i(2)} + U''_{i(2)} \cdot I''_{i(2)} \right) \tag{A.11}$$

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Determine the additional load losses:

$$P_{\mathrm{Lr}} = k \cdot \left[(1 - s) \cdot \left(P_{\delta(1)} - P_{\delta(2)} \right) - P_{\mathrm{fw}} \right] \tag{A.12}$$

where $k = \dfrac{1}{1 + \left(I_{\mathrm{i(1)}} / I_{\mathrm{i(2)}} \right)^2}$

Annex B
(informative)

Types of excitation systems

The types of excitation systems considered for determination of the exciter losses are:

a) shaft driven exciter

A DC or AC exciter machine is driven by the shaft of the main unit, directly or through a gear. ~~When~~ If the main unit is a synchronous machine the excitation power is supplied to the excitation winding via slip-ring and brushes.

b) brushless exciter

An AC exciter coupled to a synchronous main unit supplies the field winding directly via rotating rectifiers, avoiding slip-rings and brushes. The exciter can be a synchronous generator or an induction machine.

Excitation power of a synchronous exciter is derived either from a directly coupled AC pilot exciter with permanent magnet excitation, or from an auxiliary (secondary) winding in the main unit stator slots (same as in e)), or from a static supply.

An induction exciter is connected to a variable AC voltage supply.

c) separate rotating exciter

A DC or AC generator as part of a separate motor generator set supplies the excitation current to the field winding of the main unit.

d) static excitation system (static exciter)

The excitation power is supplied to the field winding of the main unit by a static source such as batteries or a static power converter-fed from a separate source.

e) excitation from auxiliary winding (auxiliary winding exciter)

The excitation power for an AC generator is provided by an auxiliary (secondary) winding in the main unit stator slots, utilizing fundamental or harmonic flux, and supplied to the field winding via rectifiers, slip-rings and brushes.

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Annex C
(informative)

Induction machine slip measurement

Rotor losses in induction machines are directly proportional to slip, with slip defined as the fractional departure of shaft speed from the synchronous speed corresponding to the supply frequency and the number of motor poles.

Slip measurements should be ratio-metric, i.e. concurrently account for both motor shaft speed and the frequency of the supply to the motor during the time interval over which those measurements are made. An example is the stroboscopic method, which uses supply-frequency-derived pulsed illumination of an induction motor shaft, and counts the number of slip revolutions over a known time period.

The following method is based on that principle, and provides very high accuracy slip measurements which can be automatically transferred to a data acquisition system.

Figure C.1 shows the principle of the measurement system, in which two pulse trains are generated: one derived directly from the shaft of an induction machine under test, and a second directly related to the frequency of the power supply. The diagram shows two sequential shaft encoders, each of which produce the same number of output pulses per revolution, connected to the shafts of an induction machine under test and a small synchronous motor connected to the same power supply, respectively.

The reference synchronous machine may be regarded as having zero slip.

The two pulse trains are fed to the inputs of a two-channel digital counter which has the facility to calculate and display the ratio of the two input frequencies.

If a motor-alternator set is used as the power supply for induction machine testing and measurements, then the second (reference) shaft encoder may be connected directly to the alternator shaft. A further possibility is that the reference frequency be generated electronically, using a phase-locked loop system.

If the ratio produced by the dual-channel counter, as above, is multiplied by the nominal synchronous speed of the reference (synchronous) motor in Figure C.1 (e.g. 1 500 min^{-1} for a 4 pole synchronous motor with a nominal supply frequency of 50 Hz), then the counter, configured as above, displays the shaft speed of the induction machine under test corrected for supply frequency, regardless of the induction machine pole number.

Slip may then be calculated directly from that indicated shaft speed.

If the two counters are started and stopped synchronously (i.e. at exactly the same times), the actual counting time is not critical. Slip measurement should be made over the same averaging time as the other measurements of motor voltage, current, electrical power and torque.

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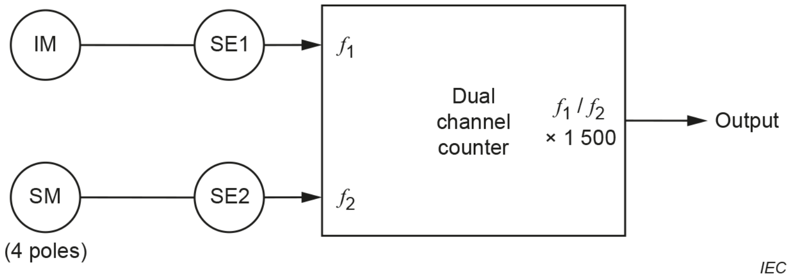

Key

IM	Induction machine under test (any number of poles)
SM	Small synchronous motor (e.g. 4 poles) or main laboratory M-G set
SE1	Sequential shaft encoder, with e.g. 600 pulses per revolution (p.p.r.)
SE2	Sequential shaft encoder, with same no. of p.p.r. as SE1
f_1	Frequency of pulse train from SE1
f_2	Frequency of pulse train from SE2
Output	ratio f_1/f_2 × synchronous speed of SM

Figure C.1 – Slip measurement system block diagram

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Annex D
(informative)

Test report template for method 2-1-1B

Manufacturer Logo	

Date of test:		Report number:		Date of issue:	

Motor description				
Rated output power	kW		Manufacturer	
Rated voltage	V		Model Nr.	
Rated current	A		Serial Nr.	
Rated speed	min^{-1}		Duty type acc. to IEC 60034-1	
Supply frequency	Hz		Design	
Number of phases	-		Insulation class acc. to IEC 60085	
IEC 60034-30-1 (rated)	IE-Code		Max. ambient temperature °C	

Initial motor conditions			
Test resistance	R_i	Ω	
Winding temperature	θ_i	°C	
Ambient temperature	θ_a	°C	

6.1.3.2.1 Rated load test			
Test resistance	R_N	Ω	
Winding temperature	θ_N	°C	
Ambient temperature	θ_a	°C	

6.1.3.2.3 Load curve test			Test resistance before load test			R	Ω	
Rated output power		%	125%	115%	100%	75%	50%	25%
Torque	T	N.m						
Input power	P_1	W						
Line current	I	A						
Operating speed	n	min^{-1}						
Teminal voltage	U	V						
Frequency	f	Hz						
Winding temperature	θ_L	°C						
			Test resistance after load test			R	Ω	

6.1.3.2.4 No-load test					Test resistance before no-load test			R	Ω	
Rated voltage		%	110%	100%	95%	90%	60%	50%	40%	30%
Input power	P_0	W								
Line current	I_0	A								
Terminal voltage	U_0	V								
Frequency	f_0	Hz								
W. temperature	θ_0	°C								
					Test resistance after no-load test			R	Ω	

6.1.3.3 Efficiency determination								
Rated output power corr.	$P_{2,\theta}$	%	125%	115%	100%	75%	50%	25%
Output power corrected	$P_{2,\theta}$	W						
Slip corrected	$s_{,\theta}$	p.u.						
Input power corrected	$P_{1,\theta}$	W						
Iron losses	P_{fe}	W						
Frict. and wind. losses corr.	$P_{fw,\theta}$	W						
Additional-load losses	P_{LL}	W						
Stator losses corrected	$P_{s,\theta}$	W						
Rotor losses corrected	$P_{r,\theta}$	W						
Power factor	cos φ	%						
Efficiency	η	%						

Tested by: ____________________ Approved ____________________

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IEC 60085, *Electrical insulation – Thermal evaluation and designation*

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IEC 60034-2-1

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Rotating electrical machines –
Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

Machines électriques tournantes –
Partie 2-1: Méthodes normalisées pour la détermination des pertes et du rendement à partir d'essais (à l'exclusion des machines pour véhicules de traction)

IEC 60034-2-1:2024-03(en-fr)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ROTATING ELECTRICAL MACHINES –

Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

FOREWORD

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IEC 60034-2-1 has been prepared by IEC technical committee 2: Rotating machinery. It is an International Standard.

This third edition cancels and replaces the second edition of IEC 60034-2-1 published in 2014. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

Harmonization of layout and requirements with IEC 60034-2-2 and IEC 60034-2-3.

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The text of this International Standard is based on the following documents:

Draft	Report on voting
2/2165/FDIS	2/2177/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 60034 series, published under the general title *Rotating electrical machines*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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ROTATING ELECTRICAL MACHINES –

Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles)

1 Scope

This part of IEC 60034 is intended to establish methods of determining efficiencies from tests, and also to specify methods of obtaining specific losses.

This document applies to DC machines and to AC synchronous and induction machines of all sizes within the scope of IEC 60034-1 rated for mains operation.

NOTE These methods may be applied to other types of machines such as rotary converters, AC commutator motors and single-phase induction motors.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60027-1, *Letter symbols to be used in electrical technology – Part 1: General*

IEC 60034-1:2022, *Rotating electrical machines – Part 1: Rating and performance*

IEC 60034-4-1:2018, *Rotating electrical machines – Part 4-1: Methods for determining electrically excited synchronous machine quantities from tests*

IEC 60034-19, *Rotating electrical machines – Part 19:Specific test methods for DC machines on conventional and rectifier-fed supplies*

IEC 60034-29, *Rotating electrical machines – Part 29: Equivalent loading and superposition techniques – Indirect testing to determine temperature rise*

IEC 60034-30-1, *Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code)*

IEC 60051(all parts), *Direct acting indicating analogue electrical measuring instruments and their accessories*

IEC 60051-1, *Direct acting indicating analogue electrical measuring instruments and their accessories – Part 1: Definitions and general requirements common to all parts*

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3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60034-1, IEC 60051-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
efficiency
ratio of output power to input power expressed in the same units and usually given as a percentage

3.2
direct efficiency determination
method by which the determination of efficiency is made by measuring directly the input power and the output power

3.3
dual-supply back-to-back test
test in which two identical machines are mechanically coupled together, and the total losses of both machines are calculated from the difference between the electrical input to one machine and the electrical output of the other machine

3.4
indirect efficiency determination
method by which the determination of efficiency is made by measuring the input power or the output power and determining the total losses. Those losses are added to the output power, thus giving the input power, or subtracted from the input power, thus giving the output power

3.5
single-supply back-to-back test
test in which two identical machines are mechanically coupled together and are both connected electrically to the same power system. The total losses of both machines are taken as the input power drawn from the system

3.6
no-load test
test in which a machine is run as a motor providing no useful mechanical output from the shaft, or if run as a generator with its terminals open-circuited

3.7
zero power factor test
no-load test on a synchronous machine, which is over-excited and operates at a power factor very close to zero

3.8
equivalent circuit method
test on an induction machine in which the losses are determined by help of an equivalent circuit model

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3.9
test with rotor removed and reverse rotation test
combined test on an induction machine in which the additional load losses are determined from a test with rotor removed and a test with the rotor running in reverse direction to the rotating magnetic field of the stator

3.10
short-circuit test
test on a synchronous machine in which a machine is run as a generator with its terminals short-circuited

3.11
locked rotor test
test in which the rotor is locked to prevent rotation

3.12
Eh-star test
test in which the motor is run in star connection on unbalanced voltage

3.13
losses

3.13.1
total losses
P_T
difference between the input power and the output power, equivalent to the sum of the constant losses (see 3.13.2), the load losses (see 3.13.4), the additional load losses (see 3.13.5) and the excitation circuit losses (see 3.13.3)

3.13.2
constant losses
P_c
losses incorporating the sum of windage, friction and iron losses

Note 1 to entry: Although these losses change with voltage and load, they are historically called "constant" losses and the name is retained in this document.

3.13.2.1
iron losses
P_{fe}
losses in active iron and additional no-load losses in other magnetic and conductive parts

3.13.2.2
friction and windage losses
P_{fw}
losses incorporating the sum of windage and friction

3.13.2.2.1
friction losses
losses due to friction (bearings and brushes, if not lifted at rated conditions) not including any losses in a separate lubricating system

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3.13.2.2.2
windage losses
total losses due to aerodynamic friction in all parts of the machine, including power absorbed in shaft mounted fans, and in auxiliary machines forming an integral part of the machine

Note 1 to entry: Losses in a separate ventilating system should be listed separately.

Note 2 to entry: For machines indirectly or directly cooled by hydrogen, see IEC 60034-1.

3.13.3
excitation circuit losses

3.13.3.1
excitation circuit losses
P_e
sum of the excitation winding losses (see 3.13.3.2), the exciter losses (see 3.13.3.3) and, for synchronous machines, electrical brush loss (see 3.13.3.5), if any

3.13.3.2
excitation winding losses
P_f
excitation (field) winding losses are equal to the product of the exciting current I_e and the excitation voltage U_e

3.13.3.3
exciter losses
P_{Ed}
exciter losses for the different excitation systems (see Annex B) are defined as follows:

a) shaft driven exciter

exciter losses are the power absorbed by the exciter at its shaft (reduced by friction and windage losses) plus the power P_{1E} drawn from a separate source at its excitation winding terminals, minus the useful power which the exciter provides at its terminals. The useful power at the terminals of the exciter is equal to the excitation winding losses as per 3.13.3.2 plus (in the case of a synchronous machine) the electrical brush losses as per 3.13.3.5.

Note 1 to entry: If the exciter can be decoupled and tested separately its losses can be determined according to 7.1.3.2.1.5.

Note 2 to entry: Whenever the exciter makes use of separate auxiliary supplies, their consumptions are to be included in the exciter losses unless they are considered together with the main machine auxiliaries consumption.

b) brushless exciter

exciter losses are the power absorbed by the exciter at its shaft, reduced by friction and windage losses (when the relevant test is performed on the set of main machine and exciter), plus the electrical power P_{1E} from a separate source (if any) absorbed by its field winding or its stator winding (in the case of an induction exciter), minus the useful power which the exciter provides at the rotating power converter terminals.

Note 3 to entry: Whenever the exciter makes use of separate auxiliary supplies their consumptions are to be included in the exciter losses unless they are considered together with the main machine auxiliaries consumption.

Note 4 to entry: If the exciter can be decoupled and tested separately, its losses can be determined according to 7.1.3.2.1.

c) separate rotating exciter

exciter losses are the difference between the power absorbed by the driving motor, plus the power absorbed by separate auxiliary supplies, of both driving and driven machines, including the power supplied by separate source to their excitation winding terminals, and the excitation power supplied as per 3.13.3.2 and 3.13.3.4. The exciter losses may be determined according to 7.1.3.2.1.

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d) static excitation system

static exciter

excitation system losses are the difference between the electrical power drawn from its power source, plus the power absorbed by separate auxiliary supplies, and the excitation supplied as per 3.13.3.2 and 3.13.3.4.

Note 5 to entry: In the case of systems fed by transformers, the transformer losses shall be included in the exciter losses.

e) excitation from auxiliary winding

auxiliary winding exciter

exciter losses are the copper losses in the auxiliary (secondary) winding and the additional iron losses produced by increased flux harmonics. The additional iron losses are the difference between the losses which occur when the auxiliary winding is loaded and when it is unloaded.

Note 6 to entry: Because separation of the excitation component of losses is difficult, it is recommended to consider these losses as an integral part of the stator losses when determining overall losses.

In the cases c) and d) no allowance is made for the losses in the excitation source (if any) or in the connections between the source and the brushes (synchronous machine) or between the source and the excitation winding terminals (DC machine).

If the excitation is supplied by a system having components as described in b) to e) the exciter losses shall include the relevant losses of the components pertaining to the categories listed in Annex B as applicable.

3.13.3.4
separately supplied excitation power
P_{1E}
excitation power P_{1E} supplied from a separate power source is:

– for exciter types a) and b) the exciter excitation power (DC or synchronous exciter) or stator winding input power (induction exciter). It covers a part of the exciter losses P_{Ed} (and further losses in induction exciters) while a larger part of P_e is supplied via the shaft;

– for exciter types c) and d) equal to the excitation circuit losses, $P_{1E} = P_e$;

– for exciter type e) $P_{1E} = 0$, the excitation power being delivered entirely by the shaft. Also, $P_{1E} = 0$ for machines with permanent magnet excitation.

Exciter types shall be in accordance with 3.13.3.3.

3.13.3.5
brush losses (excitation circuit)
P_b
electrical brush loss (including contact loss) of separately excited synchronous machines

3.13.4
load losses

3.13.4.1
load losses
P_L
sum of the winding (I^2R) losses (see 3.13.4.2) and the electrical brush losses (see 3.13.3.5), if any

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3.13.4.2
winding losses
winding losses are I^2R losses:

– in the armature circuit of DC machines;
– in the stator and rotor windings of induction machines;
– in the armature and field windings of synchronous machines

3.13.4.3
brush losses
P_b
electrical brush loss (including contact loss) in the armature circuit of DC machines and in wound-rotor induction machines

3.13.5
additional load losses
P_{LL}
losses produced in active iron and other magnetic and conductive parts by alternating stray fluxes when the machine is loaded; eddy current losses in winding conductors caused by load current-dependent flux pulsations and additional brush losses caused by commutation

Note 1 to entry: These losses do not include the additional no-load losses of 3.13.2.2.

3.13.6
short-circuit losses
P_{sc}
current-dependent losses in a synchronous machine and in a DC machine when the armature winding is short-circuited

3.14
test quantities <polyphase AC machines>

3.14.1
terminal voltage
for polyphase AC machines, the arithmetic average of line voltages

3.14.2
line current
for polyphase AC machines, the arithmetic average of line currents

3.14.3
line-to-line resistance
for polyphase AC machines, the arithmetic average of resistances measured between each pair of terminals

Note 1 to entry: For Y-connected three-phase machines, the phase-resistance is 0,5 times the line-to-line resistance. For Δ-connected machines, the phase-resistance is 1,5 times the line-to-line resistance.

Note 2 to entry: In Clauses 6 and 7 explanations and formulae given are for three-phase machines, unless otherwise indicated.

3.14.4
temperature rise
is the machine temperature minus the cooling medium (coolant) temperature as defined by IEC 60034-1

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4 Symbols and abbreviated terms

4.1 Symbols

$\cos \varphi$	is the power factor[1]
f	is the supply frequency, Hz
I	is the line current (average of all phases), A
k_{θ}	is the temperature correction factor
n	is the operating speed, s^{-1}
p	is the number of pole pairs
P	is the power, W
P_0	is the input power at no-load, W
P_1	is the input power, excluding excitation[2], W
P_2	is the output power, W
P_b	is the brush loss, W
P_D	is the output power (shaft power) of a drive motor, W
P_e	is the excitation circuit losses, W
P_{1E}	is the excitation power supplied by a separate source, W
P_{Ed}	is the exciter losses, W
P_{el}	is the electrical power, excluding excitation, W
P_f	is the excitation (field) winding losses, W
P_{fe}	is the iron losses, W
P_{fw}	is the friction and windage losses, W
P_c	is the constant losses, W
P_L	is the load losses, W
P_{Lr}	is the residual losses, W
P_{LL}	is the additional-load losses, W
P_{sc}	is the short-circuit losses, W
P_{mech}	is the mechanical power, W
P_T	is the total losses, W
P_w	is the winding losses, W, where subscript w is generally replaced by a, f, e, s or r (see 4.2)
R	is a winding resistance, Ω
R_{eh}	is the actual value of the auxiliary resistor for the Eh-star test (see 6.2.5), Ω
R'_{eh}	is the typical value of the auxiliary resistor, Ω
R_f	is the field winding resistance, Ω

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[1] This definition assumes sinusoidal voltage and current.

[2] Unless otherwise indicated, the tests in this document are described for motor operation, where P_1 and P_2 are electrical input and mechanical output power, respectively.

R_{ll}	is the line-to-line-resistance (average of all phases), Ω
R_{ph}	is the phase-resistance (average of all phases), Ω
s	is the slip, in per unit value of synchronous speed
T	is the machine torque, N·m
T_d	is the reading of the torque measuring device, N·m
U	is the terminal voltage (average of all phases), V
U_0	is the terminal voltage at no-load (average of all phases), V
U_N	is the rated terminal voltage, V
X	is the reactance, Ω
$\underline{Z} = R + j \times X$	is the notation for a complex quantity (impedance as example)
$Z = \lvert\underline{Z}\rvert = \sqrt{R^2 + X^2}$	is the absolute value of a complex quantity (impedance as example)
Z	is the impedance, Ω
α	is a temperature coefficient
η	is the efficiency
θ_0	is the initial winding temperature, °C
θ_a	is the ambient temperature, °C
θ_c	primary coolant inlet temperature, °C
θ_w	is the winding temperature, °C
τ	is a time constant, s

4.2 Additional subscripts

The following subscripts may be added to symbols to clarify the machine function and to differentiate values.

Machine components:

a	armature
e	excitation
f	field winding
r	rotor
s	stator
w	winding
U,V,W	phase designations

Machine categories:

B	booster
E	exciter
G	generator
M	motor

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Operating conditions:

0	no-load
1	input
2	output
av	average, mean
d	dissipated
el	electrical
i	internal
sc	short circuit
L	test load
lr	locked rotor
mech	mechanical
N	rated
red	at reduced voltage
t	test
zpf	zero power factor test
θ	corrected to a reference coolant temperature.

NOTE Further additional subscripts are introduced in relevant subclauses.

5 Basic requirements

5.1 Direct and indirect efficiency determination

Tests can be grouped into the three following categories:

a) input-output power measurement on a single machine. This involves the direct measurement of electrical or mechanical power into, and mechanical or electrical power out of a machine;

b) electrical input and output measurement on two identical machines mechanically connected back-to-back. This is done to eliminate the measurement of mechanical power into or out of the machine;

c) determination of the actual loss in a machine under a particular condition. This is usually not the total loss but comprises certain loss components.

The methods for determining the efficiency of machines are based on a number of assumptions. Therefore, it is not recommended that a comparison be made between the values of efficiency obtained by different methods, because the figures may not necessarily agree.

5.2 Uncertainty

Uncertainty as used in this standard is the uncertainty of determining a true efficiency. It reflects variations in the test procedure and the test equipment.

Although uncertainty shall be expressed as a numerical value, such a requirement needs sufficient testing to determine representative and comparative values.

5.3 Preferred methods and methods for customer-specific acceptance tests, field-tests or routine-tests

It is difficult to establish specific rules for the determination of efficiency. The choice of test to be made depends on the information required, the accuracy required, the type and size of the machine involved and the available field test equipment (supply, load or driving machine).

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In the following, the test methods suitable for asynchronous and synchronous machines are separated into preferred methods and methods for customer-specific acceptance tests, field-tests or routine tests.

5.4 Power supply

5.4.1 Voltage

The supply voltage shall be in accordance with 7.2 (and 8.3.1 for thermal tests) of IEC 60034-1:2022.

5.4.2 Frequency

During tests, the average supply frequency shall be within ±0,1 % of the frequency required for the test being conducted.

5.5 Instrumentation

5.5.1 General

Environmental conditions shall be within the recommended range given by the instrument manufacturer. If appropriate, temperature corrections according to the instrument manufacturer's specification shall be made.

Digital instruments shall be used whenever possible.

For analogue instruments accuracy is generally expressed as a percentage of full scale, the range of the instruments chosen shall be as small as practical.

The full scale of the instrument, particularly the current sensors, shall be adapted to the power of the machine under test.

For analogue instruments the observed values should be in the upper third of the instrument range.

When testing electric machines under load, slow fluctuations in the output power and other measured quantities may be unavoidable. Therefore, for each load point many readings (typically many hundred readings) shall be taken automatically by a suitable digital meter over a period of several fluctuation cycles, at least 5 s but not more than 60 s and this average shall be used for the determination of efficiency.

5.5.2 Measuring instruments for electrical quantities

The measuring instruments shall have the equivalent of an accuracy class of 0,2 in case of a direct test and 0,5 in case of an indirect test in accordance with IEC 60051. The measuring equipment shall reach a maximum overall uncertainty of 0,2 % of reading at power factor 1,0 and shall include all errors of instrument transformers or transducers, if used.

NOTE For a routine test as described in IEC 60034-1 an accuracy class of 0,5 is sufficient.

In the case of AC machines, unless otherwise stated in this standard, the arithmetic average of the line currents and voltages shall be used.

5.5.3 Torque measurement

The torque measuring device shall have a minimum class of 0,2. The minimum torque measured shall be at least 10 % of the torque meter’s nominal torque. This applies also to part load measurements, because of increased instrument uncertainty at small readings. If a better class instrument is used, the allowed torque range can be extended accordingly.

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NOTE For example class 0,1 means 5 % of the torque meter's nominal torque.

Allowed torque measuring device are an inline torque meter or a reaction torque sensor between the machine and its base. In the latter case the machine is directly coupled to the load. See Figure 2.

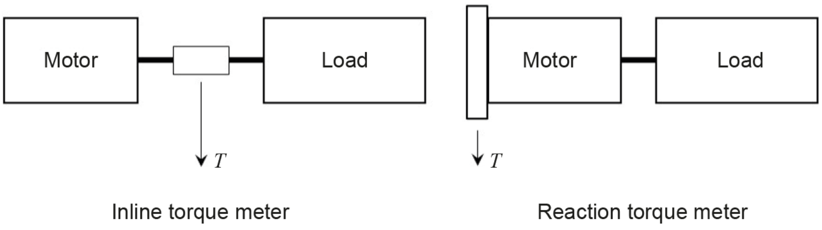

Figure 1 – Torque measuring devices

It shall be noted that the temperature of the torque sensor (i.e., due to proximity to the rotor) may be higher than the ambient temperature and is acknowledged to have a significant contribution to overall uncertainty. In that case the contribution of temperature to the uncertainty shall be limited to 0,15 % of full scale. If that is not practical, an appropriate temperature correction shall be applied.

Parasitic loads should be minimized by shaft alignment and the use of flexible couplings.

5.5.4 Speed and frequency measurement

The instrumentation used to measure supply frequency shall have an accuracy of ±0,1 % of full scale. The speed measurement should be accurate within 0,1 revolution per minute.

NOTE For asynchronous machines, the measurement of slip by a suitable method may replace speed measurement (see Annex C).

5.5.5 Temperature measurement

The instrumentation used to measure temperatures shall have an accuracy of ±1 K.

5.6 Units

Unless otherwise specified, the units of values are SI-units as listed in IEC 60027-1.

5.7 Resistance

5.7.1 Test resistance

Winding resistance R is the ohmic value, determined by appropriate methods.

For DC machines, R is the total resistance of all windings carrying armature current (armature, commutation, compensating winding, compound winding).

For DC and synchronous machines, R_f is the field winding resistance.

For polyphase AC machines, $R = R_{ll}$ is the line-to-line average resistance of the stator or armature winding according to 3.14.3. In the case of wound rotor induction machines, $R_{r,ll}$ is the rotor line-to-line average resistance.

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The measured resistance at the end of the thermal test shall be determined as soon as possible but not after more than twice the interval as specified in Table 6 of IEC60034-1:2022. Additional readings shall be taken at intervals of approximately 1 min until these readings have begun a distinct decline from their maximum value. A curve of these readings shall be plotted as a function of time and extrapolated to zero. The value of temperature thus obtained shall be considered as the temperature at shutdown.

The measured temperature of windings shall be determined according to 5.7.2.

5.7.2 Winding temperature

The measured winding temperature shall be determined by one of the following methods (shown in order of preference):

a) temperature determined from the rated load test resistance R_N by the extrapolation procedure as described in 5.7.1;

b) temperature measured directly by either ETD or thermocouple; if the temperature is measured by more than one ETD or thermocouple, the average of all readings shall be taken;

c) temperature determined according to a) on a duplicate machine of the same construction and electrical design;

d) if load capability is not available, determine operating temperature according to IEC 60034-29;

e) if the rated load test resistance R_N cannot be measured directly, the winding temperature shall be assumed to be equal to the reference temperature of the rated thermal class as given in Table 1.

Table 1 – Reference temperature

Thermal class of the insulation system	Reference temperature °C
130 (B)	95
155 (F)	115
180 (H)	135

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If the rated temperature rise or the rated temperature is specified as that of a lower thermal class than that used in the construction, the reference temperature shall be that of the lower thermal class.

Motors that are subject to check testing for regulatory purposes are not to be dismantled. In that case, measurement of winding temperature shall be by the change of resistance method;

5.7.3 Correction to reference coolant temperature

If required, the winding resistance values recorded during test shall be referred to a standard reference temperature of 25 °C. The correction factor to adjust the winding resistance (and the slip in the case of cage induction machines) to a standard reference coolant temperature of 25 °C shall be determined by

$$k_\theta = \frac{235 + \theta_w + 25 - \theta_c}{235 + \theta_w} \qquad (1)$$

where

k_θ is the temperature correction factor for windings;

θ_c is the primary coolant temperature during test;

θ_w is the winding temperature according to 5.7.2.

The temperature constant 235 is for copper; this should be replaced by 225 for aluminium conductors.

For machines with water as the primary or secondary coolant, the water reference temperature shall be 25 °C according to Table 5 of IEC 60034-1:2022. Alternative values may be specified by agreement.

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5.8 State of the machine under test and test categories

Tests shall be conducted on an assembled machine with the essential components in place, to obtain test conditions equal or very similar to normal operating conditions.

For handling of sealing systems for efficiency classification related measurements see IEC 60034-30-1.

It is preferable that the machine be selected randomly from series production without special considerations.

The sub-tests that make up a test procedure shall be performed in the sequence listed. It is not essential that the tests be carried out immediately one after another. However, if the sub-tests are performed with delay, then the specified thermal conditions shall be re-established prior to obtaining the test data.

For machines with adjustable brushes, the brushes shall be placed in the position corresponding to the specified rating. For induction motors with wound rotor having a brush lifting device, the brushes shall be lifted during tests, with the rotor winding short-circuited. For measurements on no-load, the brushes shall be placed in the neutral axis on DC machines.

For machines having brushes, during the rated load test, and prior to any measurement, a visual inspection shall be done to check if the brushes are fully bedded, and a proper skin is developed.

The bearing losses depend on the operating temperatures of the bearings, the type of lubricant and lubricant temperature.

If the losses in a separate lubricating system of bearings are required these should be listed separately.

In the case of motors which are furnished with thrust bearings, only that portion of the thrust bearing loss produced by the motor itself shall be included in the total losses.

Friction losses due to thrust load may be included by agreement.

If the tested machine uses direct flow cooling of the bearings, these losses are distributed between the tested machine and any other one coupled to it mechanically, such as a turbine, in proportion to the masses of their rotating parts. If there is no direct flow cooling, the distribution of bearing losses shall be determined from empirical formulae by agreement.

5.9 Excitation circuit measurements

Determination of voltage U_e and current I_e (see 3.13.3.2) depends on the configurations of the excitation system (see 3.13.3.3). Where applicable, test data shall be recorded according to the following:

a) for machines excited by shaft driven, separate rotating, static and auxiliary winding exciters (see 3.13.3.3 a), c), d) and e)), voltage U_e and current I_e are measured:
   - at the excitation winding terminals of DC machines;
   - at the field winding slip-rings of synchronous machines;

b) for machines excited by brushless exciters (see 3.13.3.3 b)), test data shall be recorded by either of the following methods:
   - voltage U_e measured using auxiliary (provisional) slip-rings connected to the field winding ends. From the voltage and resistance R_e determine the field winding current $I_e = \frac{U_e}{R_e} = \frac{U_f}{R_f}$. The field winding resistance is to be measured after switching off the machine using the extrapolation procedure according to 5.7.1;
   - voltage U_e and current I_e measured using power slip-rings suitable for direct measurement of field winding current.

NOTE The difference between U_e and U_f (voltage drop of brushes) is in practice almost negligible.

Voltages and currents shall be measured at stabilized temperatures.

The excitation circuit losses P_e are determined according to 7.1.3.2.1.5 (synchronous machines) or 8.3.2.1.5 (DC machines).

5.10 Ambient temperature during testing

The ambient temperature should be in the range of 15 °C to 40 °C.

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6 Test methods for the determination of the efficiency of induction machines

6.1 Preferred testing methods

6.1.1 General

This document defines three different preferred methods with low uncertainty within the given range of application, see Table 2. The specific method to be used depends on the type or rating of the machine under test:

Method 2-1-1A: Direct measurement of input and output power by using a torque measuring device. To be applied for all single phase machines.

Method 2-1-1B: Summation of separate losses. Additional load loss determined by the method of residual loss. To be applied for all three phase machines with rated output power up to 2 MW. See also Annex D.

Method 2-1-1C: Summation of separate losses. Additional load loss determined by the method of assigned value. To be applied for all three phase machines with rated output power greater than 2 MW.

Table 2 – Induction machines: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-1A	**Direct measurement:** **Input-output**	Torque measurement	6.1.2	All single phase machines	Torque measuring device for full-load
2-1-1B	**Summation of losses:** **Residual losses**	P_{LL} determined from residual loss	6.1.3	Three phase machines with rated output power up to 2 MW	Torque measuring device for 1,25 × full-load, or load machine for 1,25 × full-load with torque measuring device
2-1-1C	**Summation of losses:** **Assigned value**	P_{LL} from assigned value	6.1.4	Three phase machines with rated output power greater than 2 MW	

6.1.2 Method 2-1-1A – Direct measurement of input and output

6.1.2.1 General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the stator is measured in the same test.

Input and output power are:

in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 2); (2)

in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$ (3)

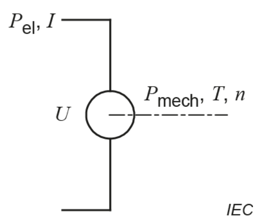

Figure 2 – Sketch for torque measurement test

For an overview, Figure 3 provides a flowchart for efficiency determination by this test method.

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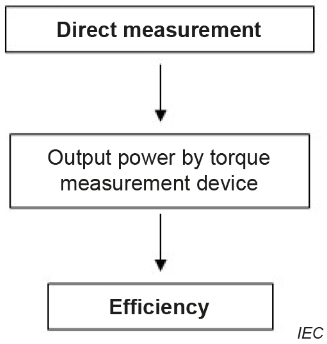

Figure 3 – Efficiency determination according to method 2-1-1A

6.1.2.2 Test procedure

Couple the machine under test to a load machine with torque measuring device. Operate the machine under test at the required load until thermal equilibrium is achieved (rate of change 1 K or less per half hour).

Record U, I, P_{el}, n, T, θ_c.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

6.1.2.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1} \tag{4}$$

Input power P_1 and output power P_2 are:

in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$; (5)

in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$ (6)

where

$$P_{mech} = 2\pi \times T \times n \tag{7}$$

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6.1.3 Method 2-1-1B – Summation of losses, additional load losses according to the method of residual loss

6.1.3.1 General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

- iron loss;
- windage and friction losses;
- stator and rotor copper losses;
- additional load losses.

For an overview, Figure 4 provides a flowchart for efficiency determination by this test method.

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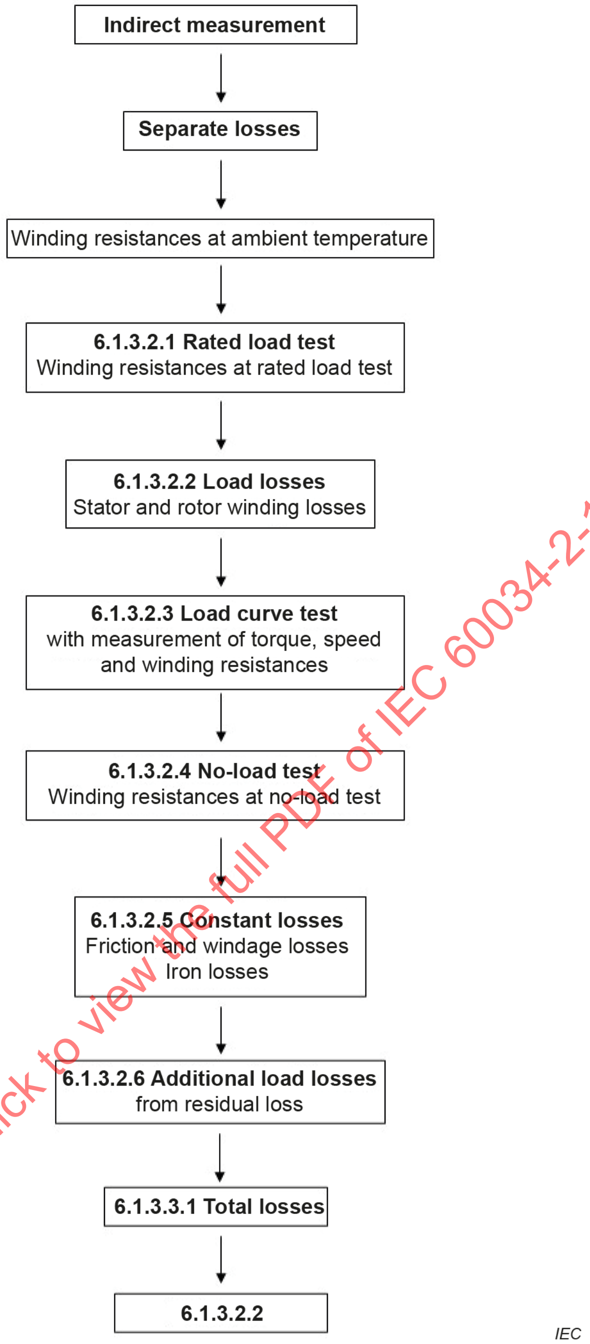

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Figure 4 – Efficiency determination according to method 2-1-1B

6.1.3.2 Test procedure

6.1.3.2.1 Rated load test

Before this load test, measure the temperature and the winding resistance of the motor with the motor at ambient temperature.

The machine shall be loaded by suitable means with rated output power and operated until thermal equilibrium is achieved (rate of change 1 K or less per half hour). Record the following quantities:

– P_1, T, I, U, n, f, θ_c, θ;

– $R_N = R$ (the test resistance for rated load according to 5.7.1);

– θ (the winding temperature at rated load according to 5.7.2).

Immediately after the load test, the drift of the torque transducer shall be checked. In case of a deviation above the allowed tolerance of the transducer, adjust it and repeat the measurements.

6.1.3.2.2 Load losses

6.1.3.2.2.1 Stator-winding losses and temperature correction

The uncorrected stator-winding losses at rated load are:

$$P_s = 1{,}5 \times I^2 \times R \tag{8}$$

where I and R are determined in 5.7.1.

Determine the stator-winding losses, using the stator winding resistance R_N from the rated load test, corrected to a reference coolant temperature of 25 °C:

$$P_{s,\theta} = P_s \times k_\theta \tag{9}$$

where k_θ is the correction according to 5.7.3 for the stator winding.

6.1.3.2.2.2 Rotor winding losses and temperature correction

For the uncorrected rotor winding losses use the formula:

$$P_r = (P_1 - P_s - P_{fe}) \times s \tag{10}$$

where

$$s = 1 - \frac{p \times n}{f} \tag{11}$$

P_1, n and f are according to the rated load test;

P_s according to the load test as stated above;

P_{fe} is according to 6.1.3.2.5.

The corrected rotor winding losses are determined using the corrected value of the stator winding losses:

$$P_{r,\theta} = (P_1 - P_{s,\theta} - P_{fe}) \times s_\theta$$

where

P_{fe} is according to 6.1.3.2.5 for a reference coolant temperature of 25 °C;

$s_\theta = s \times k_\theta$ is the slip corrected to a reference coolant temperature of 25 °C (see 5.7.3);

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k_θ is the correction according to 5.7.3.

6.1.3.2.2.3 Temperature correction of input power (for a motor)

With the corrected stator and rotor winding losses, the corrected input power is:

$$P_{1,\theta} = P_1 - (P_s - P_{s,\theta} + P_r - P_{r,\theta}) \tag{12}$$

6.1.3.2.3 Load curve test

This test shall be carried out immediately after the rated load test with the motor at operating temperature.

If that is not possible, prior to the start of recording data for this test, the temperature rise of the windings shall be within 5 K of the initial temperature rise θ_N, obtained from a rated load temperature test.

Apply the load (shaft power) to the machine at the following six load points: approximately 125 %, 115 %, 100 %, 75 %, 50 % and 25 % of rated load. These tests shall be performed as quickly as possible to minimize temperature changes in the machine during testing.

NOTE 1 As an indication, the applied load may vary by ± 5 % from the figures given above. The impact on the further evaluation of the residual losses is limited.

Supply frequency variation between all points shall be less than 0,1 %.

Measure R before the highest and after the lowest load reading. The resistance for 100 % load and higher loads shall be the value determined before the highest load reading. The resistance used for loads less than 100 % shall then be determined as varying linearly with load, using the reading before the test for the highest load and after the lowest reading for 25 % load.

NOTE 2 Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each load point may then be determined from measured resistance before load curve test multiplied with the ratio of the temperature of the winding at that load point to the temperature of the winding measured before the start of the test.

Record for each load point: U, I, P_1, n, f, T.

The stator-winding losses at each of the load points are:

$$P_s = 1{,}5 \times I^2 \times R \tag{13}$$

where I and R are determined according to 6.1.3.2.2 for each load point.

For the rotor winding losses for each of the load points use the formula:

$$P_r = (P_1 - P_s - P_{fe}) \times s \tag{14}$$

where

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$$s = 1 - \frac{p \times n}{f} \tag{15}$$

P_1, n and f are according to the load curve test;

P_s is according to the load curve test as stated above;

P_{fe} is according to 6.1.3.2.5.

6.1.3.2.4 No-load test

The no-load test shall be carried out on a hot machine immediately after the load curve test.

Alternatively, the test may also be carried out with stabilized no-load losses. The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at the following eight values of voltage, including rated voltage, so that:

– the values at approximately 110 %, 100 %, 95 % and 90 % of rated voltage are used for the determination of iron losses;
– the values at approximately 60 %, 50 %, 40 % and 30 % of rated voltage are used for the determination of windage and friction losses.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linearly with the electrical power P_0.

For induction machines R_0 is $R_{ll,0}$. Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

NOTE Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each voltage point may then be determined from measured resistance before no-load test multiplied with the ratio of the temperature of the winding at that load point to the temperature of the winding measured before the start of the test.

For a coupled machine, P_0 is determined from T and n.

6.1.3.2.5 Constant losses

6.1.3.2.5.1 General

Subtracting the no-load winding losses from the no-load input power gives the constant losses that are the sum of the friction, windage and iron losses. Determine the constant losses for each value of voltage recorded.

$$P_c = P_0 - P_s = P_{fw} + P_{fe} \tag{16}$$

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where

$$P_s = 1{,}5 \times I_0^2 \times R_{ll,0} \qquad (17)$$

with $R_{ll,0}$ being the interpolated winding resistance at each voltage point.

6.1.3.2.5.2 Friction and windage losses

From the four or more consecutive no-load loss points between approximately 60 % of voltage and 30 % of voltage develop a curve of constant losses (P_c) against the voltage squared (U_0^2).

Extrapolate a straight line to zero voltage. Determine the intercept at zero voltage, which is considered the friction and windage losses P_{fw0} at approximately synchronous speed.

6.1.3.2.5.3 Iron losses

From the values of voltage between approximately 90 % and 110 % of rated voltage, develop a curve of $P_{fe} = P_c - P_{fw}$ against voltage U_0.

To determine the iron losses at full load the inner voltage U_i that takes the resistive voltage drop in the primary winding into account shall be calculated:

$$U_i = \sqrt{\left(U - \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \sin\varphi\right)^2} \quad \text{for a motor} \qquad (18)$$

$$U_i = \sqrt{\left(U + \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \sin\varphi\right)^2} \quad \text{for a generator} \qquad (19)$$

Where

$$\cos\varphi = \frac{P_1}{\sqrt{3} \times U \times I}; \quad \sin\varphi = \sqrt{1 - \cos^2\varphi} \qquad (20)$$

U, P_1, I and R are from the load test according to 6.1.3.2.1.

The iron losses at full load shall be interpolated from the iron losses over voltage U_0 curve at the voltage U_i.

NOTE The iron losses at full load may be calculated by using the ratio $(U_i/U_N)^2$ applied to the iron losses at no-load.

Because the stator leakage inductance is unknown, the voltage is only considering the resistive voltage drop. Due to the low power factor at no-load, the resistive voltage drop is negligible during the measurement itself and shall only be taken into consideration for the load values.

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6.1.3.2.6 Additional load losses P_{LL}

6.1.3.2.6.1 Residual losses P_{Lr}

The residual losses shall be determined for each load point by subtracting from the input power: the mechanical output power, the uncorrected stator winding losses at the resistance of the test, the adjusted iron losses, the corrected windage and friction losses, and the uncorrected rotor winding losses corresponding to the determined value of slip.

The iron losses at each load point shall be interpolated from the iron losses over voltage U_0 curve at the voltage U_i for the respective load point.

$$P_{Lr} = P_1 - P_2 - P_s - P_r - P_{fe} - P_{fw}\,; \tag{21}$$

$$P_2 = 2\pi \cdot T \cdot n \text{ for a motor and } P_1 = 2\pi \cdot T \cdot n \text{ for a generator.} \tag{22}$$

where

$$P_{fw} = P_{fw0} \cdot (1-s)^{2,5} \text{ with } s = 1 - \frac{p \times n}{f} \tag{23}$$

are the corrected friction and windage losses.

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6.1.3.2.6.2 Smoothing of the residual loss data

The residual loss data shall be smoothed by using the linear regression analysis (see Figure 5) based on expressing the losses as a function of the square of the load torque according to the relationship:

$$P_{Lr} = A \times T^2 + B \tag{24}$$

A and B are constants determined from the six load points using the following formulas:

A is the slope according to

$$A = \frac{i \cdot \sum\left(P_{Lr} \cdot T^2\right) - \sum P_{Lr} \cdot \sum T^2}{i \cdot \sum\left(T^2\right)^2 - \left(\sum T^2\right)^2} \tag{25}$$

B is the intercept according to

$$B = \frac{\sum P_{Lr}}{i} - A \cdot \frac{\sum T^2}{i} \tag{26}$$

i is the number of load points summed.

The intercept B should be considerably smaller (< 50 %) than the additional load losses P_{LL} at rated torque. Otherwise the measurement may be erroneous and should be checked.

NOTE The intercept B may be positive or negative. Figure 5 shows an example for positive intercept B.

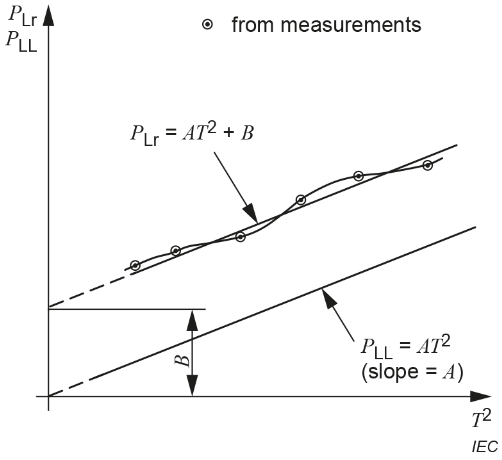

Figure 5 – Smoothing of the residual loss data

The correlation coefficient is calculated as

$$\gamma = \frac{i \cdot \Sigma\left(P_{Lr} \cdot T^2\right) - \left(\Sigma P_{Lr}\right) \cdot \left(\Sigma T^2\right)}{\sqrt{\left(i \cdot \Sigma\left(T^2\right)^2 - \left(\Sigma T^2\right)^2\right) \cdot \left(i \cdot \Sigma P_{Lr}^2 - \left(\Sigma P_{Lr}\right)^2\right)}} \qquad (27)$$

If the correlation coefficient γ is less than 0,95, delete the worst point and repeat the regression. If γ increases to ≥ 0,95, use the second regression; if γ remains less than 0,95, the test is unsatisfactory and errors in the instrumentation or test readings, or both, are indicated. The source of the error should be investigated and corrected, and the test should be repeated. In case of sufficient test data, a correlation coefficient of 0,98 or better is likely.

If the slope constant A is established, a value of additional load losses for each load point shall be determined by using the formula:

$$P_{LL} = A \times T^2 \qquad (28)$$

6.1.3.3 Efficiency determination

6.1.3.3.1 Total losses

The total losses shall be taken as the sum of the adjusted iron losses, the corrected friction and windage losses, the load losses and the additional load losses:

$$P_T = P_{fe} + P_{fw} + P_{s\,\theta} + P_{r\,\theta} + P_{LL}, \qquad (29)$$

where

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$$P_{fw} = P_{fw0} \cdot (1 - s_{\theta})^{2,5} \tag{30}$$

are the corrected friction and windage losses.

6.1.3.3.2 Efficiency

The efficiency is determined from

$$\eta = \frac{P_{1,\theta} - P_T}{P_{1,\theta}} = \frac{P_2}{P_2 + P_T} \tag{31}$$

NOTE Usually, the first expression is preferred for a motor, the second one for a generator.

where

$P_{1,\theta}$ is the temperature corrected input power from the rated load test;

P_2 is the output power from the rated load test.

6.1.4 Method 2-1-1C – Summation of losses with additional load losses from assigned allowance

6.1.4.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. For the reason that full load testing as required by method 2-1-1B is in general not practical for ratings above 2 MW, this method is based on a load test with reduced voltage and an assigned value for the additional load losses. Therefore the full load test and the load curve test are not required for method 2-1-1C.

Apart from this, method 2-1-1C is similar to method 2-1-1B.

For an overview, Figure 6 provides a flowchart for efficiency determination by this test method.

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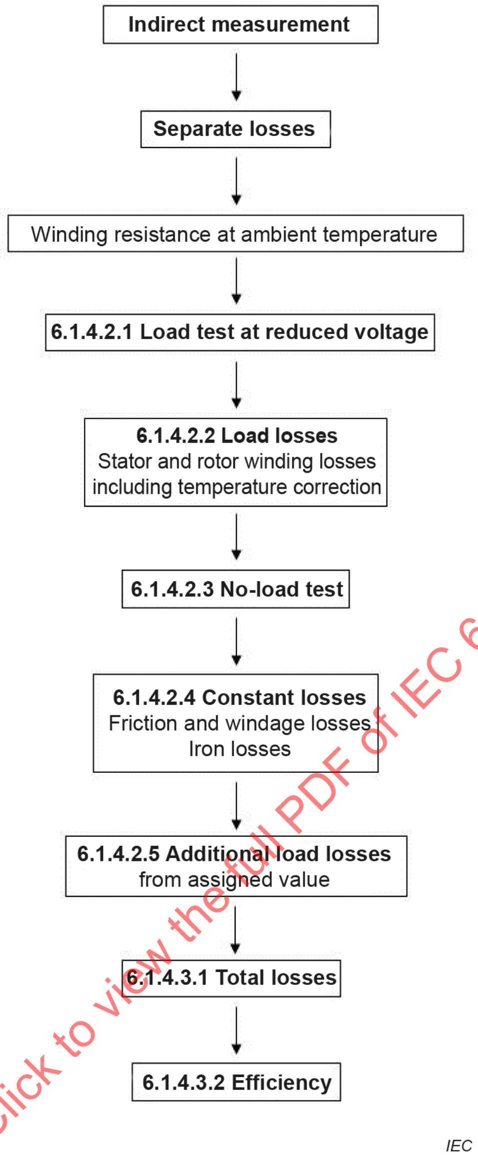

Figure 6 – Efficiency determination according to method 2-1-1C

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6.1.4.2 Test procedure

6.1.4.2.1 Load test at reduced voltage

For large machines which cannot be tested at full load, the load test at reduced voltage is an appropriate method. The following are required: a load test with the machine acting as a motor at reduced voltage U_{red} at rated speed, a no-load test at the same reduced voltage U_{red}, and a no-load test at rated voltage and rated frequency.

Using this method, it is assumed that at reduced voltage, while keeping the speed constant, currents diminish as the voltage and power diminishes as the square of the voltage.

Operate the machine using the maximum available load with a decrease in voltage to achieve rated speed. Operate to achieve thermal equilibrium.

At reduced voltage, record: U_{red}, I_{red}, P_{1red}, I_{0red}, $\cos(\varphi_{0red})$.

At rated voltage and no-load, record: U_N, I_0, $\cos(\varphi_0)$.

From the result of such a test calculate the current under load and the absorbed power at rated voltage:

$$\underline{I} = \underline{I}_{red} \frac{U_N}{U_{red}} + \Delta \underline{I}_0 \tag{32}$$

where

$$\Delta \underline{I}_0 = -j\left(\left|\underline{I}_0\right| \sin \varphi_0 - \left|\underline{I}_{0,red}\right| \frac{U_N}{U_{red}} \sin \varphi_{0,red}\right) \tag{33}$$

$$P_1 = P_{1,red} \times \left(\frac{U_N}{U_{red}}\right)^2 \tag{34}$$

NOTE Underlined current symbols indicate vectors (see Figure 7).

By means of the values I and P_1 thus determined, and with the slip measured at reduced voltage, it is possible to calculate the load losses, similar to a load test at rated voltage.

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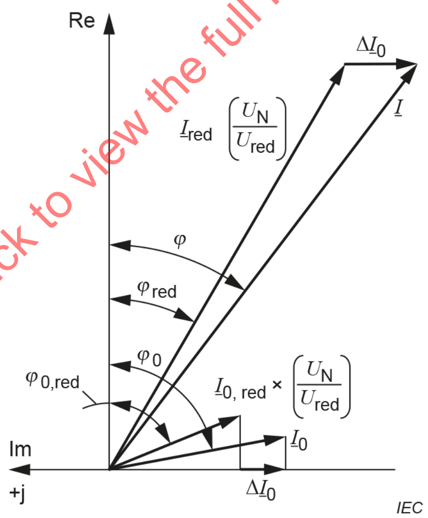

Figure 7 – Vector diagram for obtaining current vector from reduced voltage test

6.1.4.2.2 Load losses

The determination of load losses is similar to 6.1.3.2.2.

6.1.4.2.3 No-load test

The no-load test shall be carried out on a hot machine immediately after the load test.

The no-load test is similar to 6.1.3.2.4.

6.1.4.2.4 Constant losses

The determination of the constant losses is similar to 6.1.3.2.5.

6.1.4.2.5 Additional load losses P_{LL}

The value of additional load losses P_{LL} at rated load shall be determined as a percentage of input power P_1 using the curve in Figure 8.

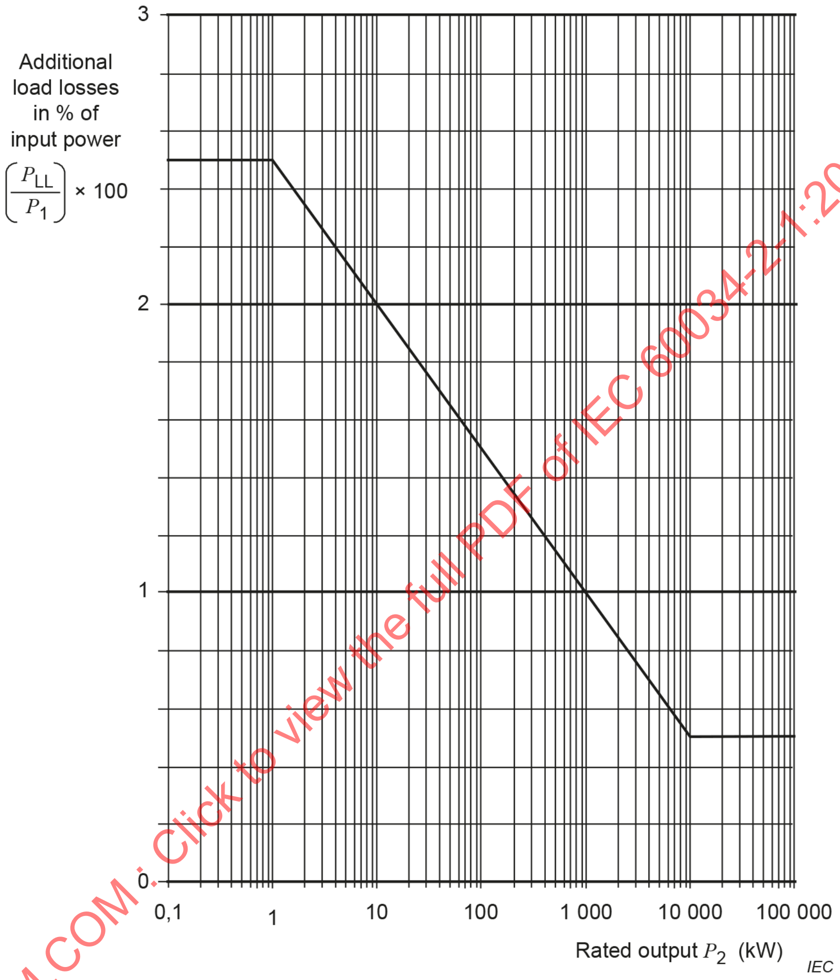

Figure 8 – Assigned allowance for additional load losses P_{LL}

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The values of the curve may be described by the following formulas:

for $P_2 \leq 1$ kW $$P_{LL} = P_1 \times 0{,}025$$

for 1 kW < P_2 < 10 000 kW $$P_{LL} = P_1 \times \left[0{,}025 - 0{,}005 \log_{10}\left(\frac{P_2}{1\,\text{kW}}\right)\right]$$

for $P_2 \geq 10\,000$ kW $$P_{LL} = P_1 \times 0{,}005$$

For other than rated loads, it shall be assumed that the additional load losses vary as the square of the primary current minus the square of the no-load current:

$$P_{\mathrm{LL}}(I) = P_{\mathrm{LL}}(I_{\mathrm{N}}) \times \frac{I^2 - I_0^2}{I_{\mathrm{N}}^2 - I_{0\mathrm{N}}^2}$$

NOTE The curve does not represent an average but an upper envelope of a large number of measured values, and may in most cases yield greater additional load losses than 6.1.3.

6.1.4.3 Efficiency determination

6.1.4.3.1 Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_{\mathrm{T}} = P_{\mathrm{c}} + P_{\mathrm{s}} + P_{\mathrm{r}} + P_{\mathrm{LL}} \quad (35)$$

6.1.4.3.2 Efficiency

The efficiency is determined from

$$\eta = \frac{P_1 - P_{\mathrm{T}}}{P_1} = \frac{P_2}{P_2 + P_{\mathrm{T}}} \quad (36)$$

NOTE Usually, the first expression is preferred for a motor, the second one for a generator.

6.2 Testing methods for field or routine-testing

6.2.1 General

These test methods may be used for any test, i.e. field-tests, customer-specific acceptance tests or routine-tests.

In addition, preferred methods of Table 2 may also be used outside the power range identified in Table 2.

Methods defined by this document are given in Table 3.

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Table 3 – Induction machines: other methods

Reference	Method	Description	Subclause	Required facility
2-1-1D	Dual-supply-back-to-back	Dual-supply, back-to-back test	6.2.2	Machine set for full-load; two identical units
2-1-1E	Single-supply-back-to-back	Single-supply, back-to-back test	6.2.3	Two identical units (wound rotor)
2-1-1F	Reverse rotation	P_{LL} from removed rotor and reverse rotation test	6.2.4	Auxiliary motor with rated power up to 5 × total losses
2-1-1G	Eh-star	P_{LL} from Eh-star test	6.2.5	Winding shall be connected in star connection.
2-1-1H	Equivalent circuit	Currents, powers and slip from the equivalent circuit method, P_{LL} from assigned value	6.2.6	If test equipment for other tests is not available (no possibility of applying rated load, no duplicate machine)

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6.2.2 Method 2-1-1D – Dual supply back-to-back-test

6.2.2.1 General

For an overview, Figure 9 provides a flowchart for efficiency determination by this test method.

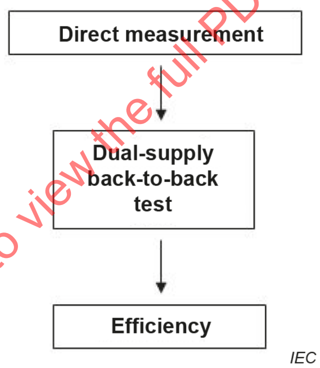

Figure 9 – Efficiency determination according to method 2-1-1D

6.2.2.2 Test procedure

Mechanically, couple two identical machines together (see Figure 10).

Tests are made with the power supplies exchanged but with the instruments and instrument transformers remaining with the same machine.

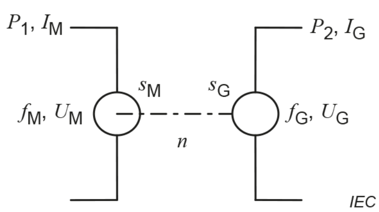

Figure 10 – Sketch for dual supply back-to-back test

Connect the driven machine (induction generator) terminals to either a machine set or a converter, supplying reactive power and absorbing active power. Supply one machine (the motor for motor rating, the generator for generator rating) with rated voltage and frequency; the second one shall be supplied with a frequency lower than that of the first machine for generator operation or higher for motor operation. The voltage of the second machine shall be that required to result in the rated voltage-to-frequency ratio.

Reverse the motor and generator connections and repeat the test.

For each test, record:

– U_M, I_M, P_1, f_M, s_M for the motor;
– U_G, I_G, P_2, f_G, s_G for the generator;
– θ_c.

6.2.2.3 Efficiency determination

If identical machines are run at essentially the same rated conditions, the efficiency shall be calculated from half the total losses and the average of motor input power and generator output power as follows:

$$\eta = 1 - \frac{P_T}{\frac{P_1 + P_2}{2}} \tag{37}$$

where

$$P_T = \frac{1}{2}(P_1 - P_2) \tag{38}$$

6.2.3 Method 2-1-1E – Single supply back-to-back-test

6.2.3.1 General

For an overview, Figure 11 provides a flowchart for efficiency determination by this test method.

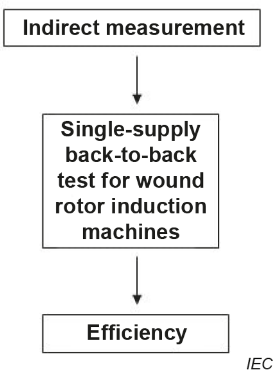

Figure 11 – Efficiency determination according to method 2-1-1E

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6.2.3.2 Test procedure

This test is applicable to wound-rotor induction machines. Mechanically couple two identical machines together and connect them both electrically to the same power supply so as to operate at rated speed and rated voltage, one as a motor and the other as a generator.

The rotor winding of the motor shall be short-circuited and the rotor winding of the generator shall be connected to a polyphase supply suitable to deliver rated rotor current at slip-frequency. The desired motor-power will be achieved by adjusting frequency and current of the lower frequency power supply.

For each test, record:

– U_1, P_1, I_1 of the power-frequency supply;

– U_r, I_r, P_r of the low-frequency supply;

– P_M absorbed at the motor terminals;

– P_G delivered at the generator terminals;

– θ_c.

6.2.3.3 Efficiency determination

If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

Calculate the efficiency from

$$\eta = 1 - \frac{P_T}{P_M} \tag{39}$$

where

P_M is the power absorbed at the terminals of the machine acting as motor;

P_T is the total losses, defined as half the total absorbed, for wound-rotor induction machines as follows: $P_T = \frac{1}{2}(P_1 + P_r)$

6.2.4 Method 2-1-1F – Summation of losses with additional load losses determined by test with rotor removed and reverse rotation test

6.2.4.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. But in this case the additional load losses are determined by a combination of two individual tests: the test with rotor removed and the reverse rotation test. Apart from that, method 2-1-1F is similar to method 2-1-1B.

For an overview, Figure 12 provides a flowchart for efficiency determination by this test method.

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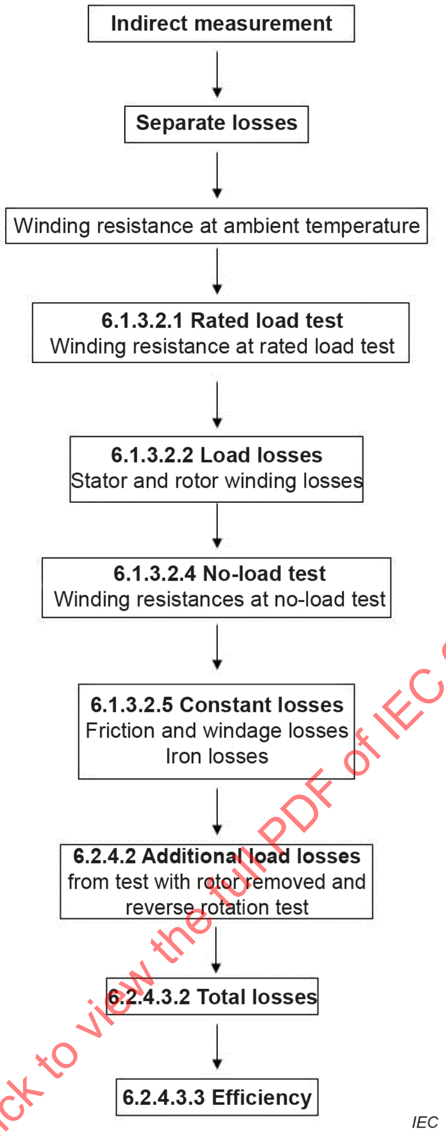

Figure 12 – Efficiency determination according to method 2-1-1F

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6.2.4.2 Test procedure

Apart from the determination of the additional load losses, the same procedures as in 6.1.3.2 shall be applied, except that the torque does not need to be measured.

The required combination of tests for the determination of the additional load losses is as follows:

a) with the rotor removed (for the fundamental frequency additional losses);

b) with the machine rotating at synchronous speed opposite to the magnetic field, driven by external means (for the higher frequencies losses).

During both tests, the stator shall be supplied by a balanced polyphase current of rated frequency for four currents between 25 % and 100 % rated current, and two currents above and of not more than 150 % rated current. Calculate the (rotor) load current I_L:

$$I_L = \sqrt{I^2 - I_0^2} \quad (40)$$

where

I is the value of stator current during the test giving a desired load current;

I_0 is the no-load current at rated voltage.

NOTE Due to lack of cooling, the current is usually limited to 125 % or 115 % for 2-pole machines to reduce the risk of overheating.

6.2.4.2.1 Test with the rotor removed

For this test, all parts in which eddy currents might be induced, for example end shields and bearing parts, shall be in place. Apply load current.

For each load current, record (symbols indexed "rm"): $P_{1,\text{rm}}$, $I_{\text{L,rm}}$, R_{rm}, $\theta_{\text{w,rm}}$.

6.2.4.2.2 Reverse-rotation test

For this test, couple a completely assembled machine to a driving motor with an output capability of not less than rated total loss and not more than five times the rated losses of the machine to be tested. For wound-rotor machines, the rotor terminals shall be short-circuited.

Drive the machine under test at synchronous speed in the direction reverse to the rotation when fed in normal phase sequence:

a) without voltage applied to the stator until friction losses are stabilized. Record: $P_{0,\text{rr}}$ supplied by the driving machine at I = 0;

b) with voltage applied to the stator to obtain stator current values equal to those for the test with rotor removed. For all test currents, record (symbols indexed "rr"): $I_{\text{L,rr}}$, R_{rr}, $P_{1,\text{rr}}$;$\theta_{\text{w,rr}}$ for the test motor; $P_{\text{D,rr}}$ of the drive motor.

The low power factor of the tests may require a phase error correction to all wattmeter readings.

6.2.4.3 Efficiency determination

6.2.4.3.1 Additional load losses

Smooth the test values of the stator powers $P_{1,\text{rm}}$ and $P_{1,\text{rr}}$, and the shaft power $\left(P_{\text{D,rr}} - P_{0,\text{rr}}\right)$ by applying a regression analysis to the log of powers and currents, resulting in the relationships below:

$$P_{1,\text{rm}} = A_{\text{rm}} \times I^{N1} + B_{\text{L,rm}};\quad P_{1,\text{rr}} = A_{\text{rr}} \times I^{N2} + B_{\text{L,rr}};\quad \left(P_{\text{D,rr}} - P_{0,\text{rr}}\right) = A_{\text{D,rr}} \times I^{N3} + B_{\text{D,rr}} \tag{41}$$

The smoothed powers will then be as follows:

$$P_{1,\text{rm}} = A_{\text{rm}} \times I^{N1};\quad P_{1,\text{rr}} = A_{\text{rr}} \times I^{N2};\quad \left(P_{\text{D,rr}} - P_{0,\text{rr}}\right) = A_{\text{D,rr}} \times I^{N3} \tag{42}$$

If the data are accurate, each curve will show a close square-law relationship between power and current.

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The additional load losses are: $P_{LL} = P_{LL,rm} + P_{LL,rr}$ where for each test current:

$$P_{LL,rm} = P_{1,rm} - \left(3 \times I^2 \times R_{s,rm}\right) \text{ is the fundamental frequency loss} \quad (43)$$

where

$R_{s,rm}$ is the stator phase resistance referred to the average of the temperatures $\theta_{W,rm}$;

$P_{LL,rr} = \left(P_{D,rr} - P_{0,rr}\right) - \left(P_{1,rr} - P_{LL,rm} - \left(3 \times I^2 \times R_{s,rr}\right)\right)$ is the higher frequencies loss

where

$R_{s,rr}$ is the stator phase resistance referred to the average of the temperatures $\theta_{W,rr}$.

The additional load loss at a specified operating point can be determined in the following steps.

a) Calculate an approximate value for the rated load current I_{NL} corresponding to the rated value of stator line current:

$$I_{NL} = \sqrt{I_N^2 - I_0^2} \quad (44)$$

where

I_N is the rated value of stator line current;

I_0 is the value of no-load stator current.

For the value of load current I_{NL}, calculate a rated value of stray load loss P_{NLL} as follows:

$$P_{NLL} = A_{Drr} \times I_{NL}^{N3} + 2A_{rm} \times I_{NL}^{N1} - A_{rr} \times I_{NL}^{N2} - 6I_{NL}^2 \times \left(R_{srm} - 0{,}5R_{srr}\right) \quad (45)$$

b) Calculate the value of load current I_L at any operating point:

$$I_L = \sqrt{I^2 - I_0^2} \quad (46)$$

where

I is the stator line current at the operating point.

c) Calculate the stray load loss P_{LL} at the operating point:

$$P_{LL} = P_{NLL} \times \left(\frac{I_L}{I_{NL}}\right)^2 \quad (47)$$

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6.2.4.3.2 Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_{T} = P_{c} + P_{s} + P_{r} + P_{LL} \tag{48}$$

6.2.4.3.3 Efficiency

The efficiency is determined from

$$\eta = \frac{P_{1} - P_{T}}{P_{1}} = \frac{P_{2}}{P_{2} + P_{T}} \tag{49}$$

where

P_1 is the input power from a rated load test;

P_2 is the output power.

6.2.5 Method 2-1-1G – Summation of losses with additional load losses determined by Eh-star method

6.2.5.1 General

As method 2-1-1B, this test method determines efficiency by the summation of separate losses. But in this case the additional load losses are determined by the Eh-star test. Apart from that, method 2-1-1G is similar to method 2-1-1B.

For an overview, Figure 13 provides a flowchart for efficiency determination by this test method.

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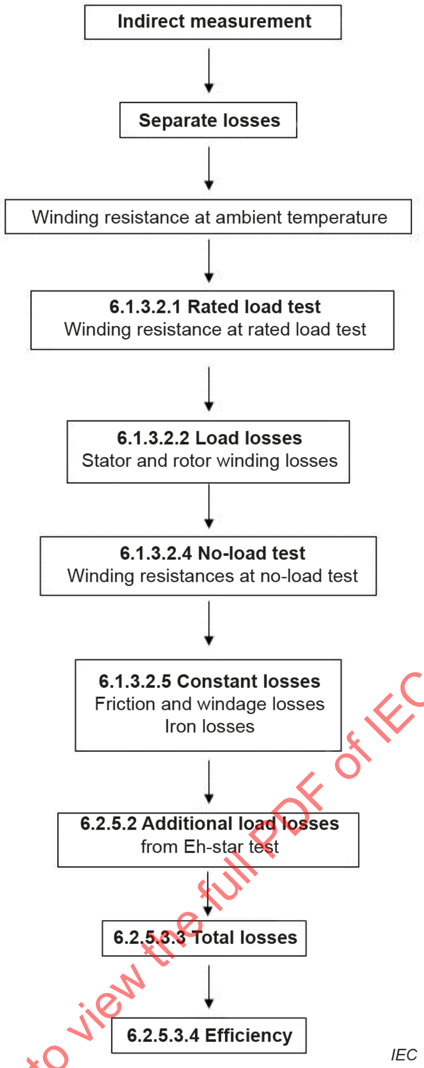

Figure 13 – Efficiency determination according to method 2-1-1G

6.2.5.2 Test procedure

Apart from the determination of the additional load losses, the same procedures as in 6.1.3.2 shall be applied.

The procedure for the determination of the additional load losses requires operating the uncoupled motor with unbalanced voltage supply. The test circuit is according to Figure 14.

Motors rated for and connected in delta-connection shall be reconnected to star-connection during this test. The star-point shall not be connected to system neutral or earth, to avoid zero-sequence currents.

The third motor-phase shall be connected to the power-line by means of a resistor R_{eh} (see Figure 14) having approximately the following typical value:

for motors rated for star-connection: $$R'_{eh} = \frac{U_N}{\sqrt{3} \cdot I_N} \cdot 0{,}2 \qquad (50)$$

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for motors rated for delta-connection: $R'_{eh} = \frac{\sqrt{3} \cdot U_N}{I_N} \cdot 0,2$ (51)

The resistor R_{eh} used during the test shall be adjusted so that the positive sequence current $I_{(1)}$ stays below 30 % of negative sequence current $I_{(2)}$ and the speed stays in the range of typical motor speeds near rated speed (see below). It is recommended to begin the test with an actual resistor R_{eh} that differs no more than 20 % from the typical value R'_{eh}.

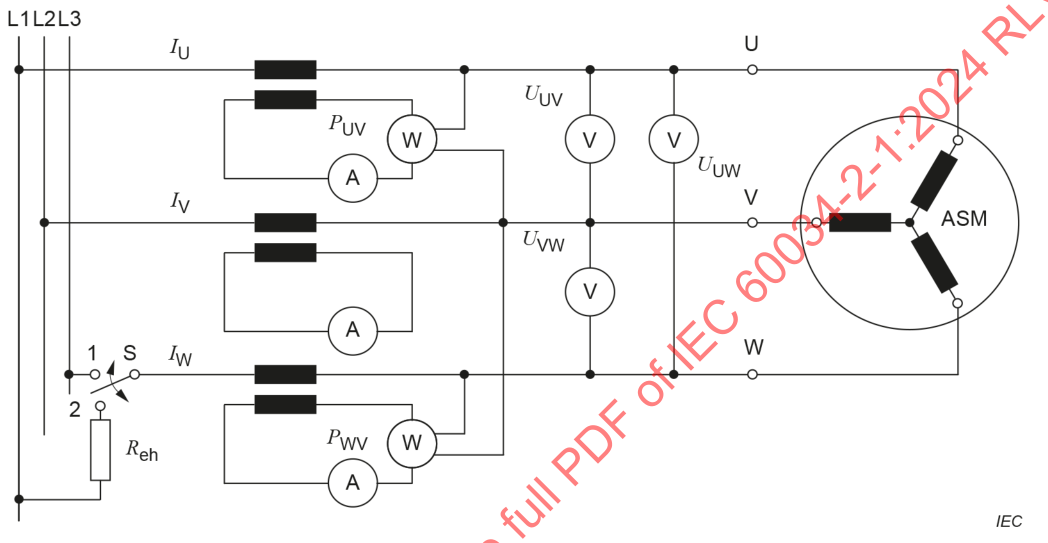

Figure 14 – Eh-star test circuit

Test current I_t is given by

for motors rated for star-connection: $I_t = \sqrt{I_N{}^2 - I_0{}^2}$ (52)

for motors rated for delta-connection: $I_t = \frac{\sqrt{I_N{}^2 - I_0{}^2}}{\sqrt{3}}$ (53)

Test voltage U_t is given by

for motors rated for star-connection: $U_t = U_N$ (54)

for motors rated for delta-connection: $U_t = U_N \cdot \sqrt{3}$ (55)

Prior to the test the no-load losses have to be stabilised according to 6.1.3.2.4.

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Measure and record the resistance between the terminals V and W (R_{VW}) before and after the complete test.

In order to avoid excessive unequal heating of the three phases, the test shall be conducted on a cold machine and carried out as quickly as possible.

Large motors can only be started without the R_{eh} resistor (switch S to position 1, see Figure 14) at reduced voltage (25 % – 40 % U_N). After run-up connect R_{eh} by switching to position 2.

Small motors should start-up with resistor R_{eh} already connected. In this case, the switch is not needed.

Vary the supply voltage for six test points. The test points shall be chosen to be approximately equally spaced between 150 % and 75 % of rated phase current measured in phase V (I_V). When starting the test, begin with the highest current and proceed in descending order to the lowest current.

The line-to-line resistance R_{VW} for 100 % test current and lower currents shall be the value determined after the lowest reading (at the end of the test). The resistance used for currents higher than 100 % shall be determined as being a linear function of current, using the readings before and after the complete test. The test resistance is determined using the extrapolation according to 5.7.1.

Record for each test point: I_U, I_V, I_W, U_{UV}, U_{VW}, U_{WU}, P_{UV}, P_{WV}, n .

It is understood that in this test no averaging of phase resistances is permissible.

NOTE Resistances may also be determined by measuring the stator winding temperature using a temperature-sensing device installed on the winding. Resistances for each load point may then be determined from the temperature of the winding at that point in relation to the resistance and temperature measured before the start of the test.

Some commonly used integrated wattmeters symmetrize the three phases by an internal virtual star connection. However, in this test the power supply is intentionally unsymmetrical. Therefore, it is essential to ensure that neither earthing of the star point nor a virtual star point is established. The provided test circuit (see Figure 14) should be strictly applied.

In order to achieve accurate results the slip shall be not greater than twice the rated slip for all currents, in other words: $n > n_{syn} - 2 \cdot (n_{syn} - n_N)$. If this condition cannot be met the test shall be repeated with an increased value of R_{eh}. If the motor still runs unstable at currents below 100 % of rated phase current these test points should be omitted.

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6.2.5.3 Efficiency determination

6.2.5.3.1 Additional load losses

For each test point calculate the values using the formulas in Annex A.

6.2.5.3.2 Smoothing of the additional-load loss data

The additional-load loss data shall be smoothed by using the linear regression analysis (see Figure 5).

The losses shall be expressed as a function of the square of the negative sequence current $I_{i(2)}$ related to test current I_t:

$$P_{\mathrm{Lr}} = A \cdot \left(\frac{I_{\mathrm{i(2)}}}{I_{\mathrm{t}}} \right)^2 + B \qquad (56)$$

A and B shall be computed similar to the procedure described in 6.1.3.2.6.

When the slope constant A is established, the value of additional load losses for rated load shall be determined by using the formula $P_{\mathrm{LL}} = A \times T^2$.

6.2.5.3.3 Total losses

The total losses shall be taken as the sum of constant losses, load losses and additional load losses:

$$P_{\mathrm{T}} = P_{\mathrm{c}} + P_{\mathrm{s}} + P_{\mathrm{r}} + P_{\mathrm{LL}} \qquad (57)$$

6.2.5.3.4 Efficiency

The efficiency is determined from

$$\eta = \frac{P_1 - P_{\mathrm{T}}}{P_1} = \frac{P_2}{P_2 + P_{\mathrm{T}}} \qquad (58)$$

NOTE Usually, the first expression is preferred for a motor, the second one for a generator.

where

P_1 is the input power from a rated load test;

P_2 is the output power.

6.2.6 Method 2-1-1H – Determination of efficiency by use of the equivalent circuit parameters

6.2.6.1 General

This method may be applied if a load test is not possible. It is based on the conventional T-model per-phase circuit of an induction machine, including an equivalent iron-loss resistor parallel to the main field reactance (see Figure 15). The rotor side parameters and quantities are referred to the stator side; this is indicated by the presence of an apostrophe ‘ at the symbols for example $X'_{\sigma\mathrm{r}}$.

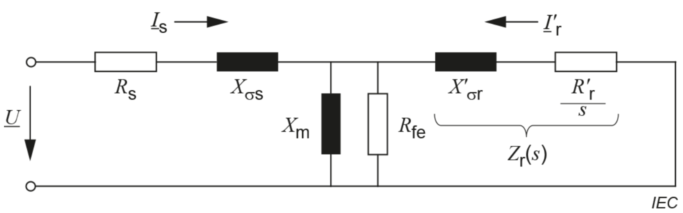

Figure 15 – Induction machine, T-model with equivalent iron loss resistor

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Application of the method to cage induction machines requires the following designed values to be available.

– $\frac{X_{\sigma s}}{X'_{\sigma r}}$ ratio of stator leakage reactance to rotor leakage reactance.

– α_r temperature coefficient of the rotor windings (conductivity referred to 0 °C).

– $X_{\sigma s}, X_m$ stator leakage and magnetizing reactances.

NOTE 1 When using the equivalent circuit method, all voltages, currents and impedances are per phase values for a three-phase machine in Y-connection; active and reactive powers are per complete machine.

NOTE 2 For copper α_r = 1/235 and for aluminium α_r = 1/225.

For an overview, Figure 16 provides a flowchart for efficiency determination by this test method.

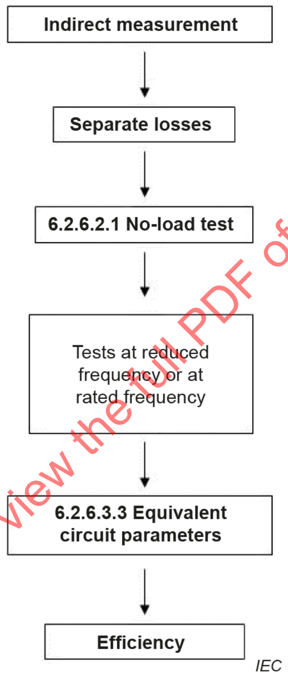

Figure 16 – Efficiency determination according to method 2-1-1H

6.2.6.2 Test procedure

6.2.6.2.1 No-load test

The no-load losses shall be stabilized at rated frequency and voltage.

The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

6.2.6.2.2 Tests at reduced frequency

With the rotor of the machine locked, supply power from a three-phase, adjustable-frequency converter capable of furnishing up to 25 % of the rated frequency at rated current. An average value of impedance shall be obtained from the position of the rotor relative to the stator.

During the tests the frequency converter, either a machine set or a static converter, should supply practically sinusoidal current at the output.

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The rotor windings of wound-rotor machines should be short-circuited for the test.

Supply rated current and take readings for at least three frequencies, including one at less than 25 % and the others between 25 % and 50 % rated frequency. During this quick test the stator winding temperature increase should not exceed 5 K.

For at least three frequencies, record: U, I, f, P_1, R_s, θ_c, θ_w.

6.2.6.2.3 Tests at rated frequency

Impedance values can also be determined from the following tests.

a) Reactance from a rated frequency, reduced voltage, rated current locked rotor test: record voltage, current, power, frequency and temperatures.

b) Rotor running resistance:

   1) from a stabilized rated frequency, rated voltage reduced load test. Record voltage, power, current, slip and temperatures for the load point; or

   2) from an open-circuit test, following a stabilized rated frequency, rated voltage no-load operation. Record the open-circuit voltage and winding temperature as a function of time after the motor is tripped from a no-load test.

NOTE This test assumes relatively low current displacement in the rotor.

6.2.6.3 Efficiency determination

6.2.6.3.1 Values from measurements

The method is based on the T-model circuit (see Figure 15).

NOTE When using the equivalent circuit method, all voltages, currents and impedances are per phase values for a three-phase machine in Y-connection; active powers and reactive powers are per complete machine.

The procedure described in this subclause is based on the test with reduced frequency. When using the test with rated frequency notice the following deviations:

a) the reactances are calculated in the same manner as in the following;

b) the rotor running resistance is determined:

   – using the test at rated frequency described in b) by reverse calculation using the equivalent circuit in Figure 15, assuming a value for R_r'. Adjust the value of R_r' until the calculated power is within 0,1 % of the measured power, or the calculated current is within 0,1 % of the measured current;

   – using the test at rated frequency described in b) by determining the time constant from the slope of the plot of the decaying voltage and the time on the open-circuit test. Determine R_r' from the formula:

$$R_r' = \frac{\left(X_m + X'_{\sigma r}\right)}{2\pi f \tau_0} \tag{59}$$

where

X_m is the magnetizing reactance;

$X'_{\sigma r}$ is the rotor leakage reactance;

f is the line frequency;

τ_0 is the open-circuit time constant.

Correct the value of R_r' to the operating temperature from the test temperature.

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6.2.6.3.2 Determine the reactive powers

– from the no-load test at rated voltage U_0 = U_N and rated frequency

$$P_{Q,0} = \sqrt{(3U_0 I_0)^2 - P_0^2} \quad (60)$$

– from the locked rotor test at reduced frequency

$$P_{Q,lr} = \sqrt{(3U\,I)^2 - P_1^2} \quad (61)$$

where

U_0, I_0 and P_0 are phase voltage, phase current and supplied power from the no-load test at rated terminal voltage;

U, I and P_1 are phase voltage, phase current and supplied power from the locked rotor impedance test at the frequencies f of this test.

6.2.6.3.3 Equivalent circuit parameters

6.2.6.3.3.1 General

The equivalent circuit parameters are determined in the following steps.

6.2.6.3.3.2 Reactances

Calculate the reactances X_m from the no-load test and $X_{\sigma s,lr}$ from the locked-rotor test at 25 % rated frequency:

$$X_m = \frac{3U_0^2}{P_{Q,0} - 3I_0^2 X_{\sigma s}} \times \frac{1}{\left(1 + \frac{X_{\sigma s}}{X_m}\right)^2} \qquad X_{\sigma s,lr} = \frac{P_{Q,lr}}{3I^2\left(1 + \frac{X_{\sigma s}}{X'_{\sigma r}} + \frac{X_{\sigma s}}{X_m}\right)} \times \left(\frac{X_{\sigma s}}{X'_{\sigma r}} + \frac{X_{\sigma s}}{X_m}\right) \quad (62)$$

$$X_{\sigma s} = \frac{f_N}{f_{lr}} X_{\sigma s,lr} \qquad X'_{\sigma r} = \frac{X_{\sigma s}}{X_{\sigma s} / X'_{\sigma r}} \quad (63)$$

Calculate using designed values as start values.

$$X_{\sigma s}, X_m \text{ and } \frac{X_{\sigma s}}{X'_{\sigma r}} \quad (64)$$

Recalculate until X_m and $X_{\sigma s}$ deviate less than 0,1 % from the values of the preceding step.

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6.2.6.3.3.3 Iron loss resistance

Determine the resistance per phase equivalent to the iron losses at rated voltage from

$$R_{\text{fe}} = \frac{3U_{\text{N,ph}}^2}{P_{\text{fe}}} \times \frac{1}{\left(1+\dfrac{X_{\sigma\text{s}}}{X_{\text{m}}}\right)^2} \quad (65)$$

where

P_{fe} is the iron losses according to the procedure given in 6.1.3.2.5 from P_0 at rated voltage.

6.2.6.3.3.4 Rotor resistance

Determine the uncorrected rotor resistance for each locked rotor impedance test point:

$$R'_{\text{r,lr}} = \left(\frac{P_1}{3I^2} - R_{\text{s}}\right) \times \left(1+\frac{X'_{\sigma\text{r}}}{X_{\text{m}}}\right)^2 - \left(\frac{X'_{\sigma\text{r}}}{X_{\sigma\text{s}}}\right)^2 \times \frac{X_{\sigma\text{s,lr}}^2}{R_{\text{fe}}} \quad (66)$$

where

R_{s} is the stator winding resistance per phase at the corresponding temperature θ_{W}.

NOTE If the rotor winding temperature deviates much from the stator winding temperature the method will become inaccurate.

The rotor resistance corrected to reference temperature (see 5.7.2, and Table 1) is, for each locked rotor impedance test frequency, given by

$$R''_{\text{r,lr}} = R'_{\text{r,lr}} \times \frac{1+\alpha_{\text{r}}\theta_{\text{ref}}}{1+\alpha_{\text{r}}\theta_{\text{W}}} \quad (67)$$

Plot a curve of $R''_{\text{r,lr}}$ values against frequency f_{lr}. The intercept with f_{lr} = 0 results in the stator referred rotor resistance R'_{r}.

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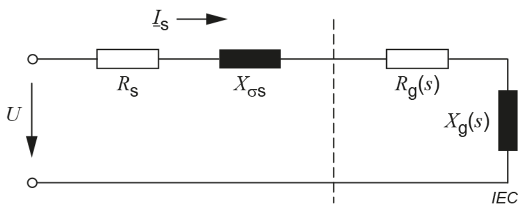

Figure 17 – Induction machines, reduced model for calculation

6.2.6.3.3.5 Load dependent impedances

For each desired load point intermediate, calculate slip dependent impedance and admittance values (see Figure 17):

$$Z_r = \sqrt{\left(\frac{R_r^{'}}{s}\right)^2 + X_{\sigma r}^{'2}} \qquad Y_g = \sqrt{\left(\frac{R_r^{'}/s}{Z_r^2} + \frac{1}{R_{fe}}\right)^2 + \left(\frac{X_{\sigma r}^{'}}{Z_r^2} + \frac{1}{X_m}\right)^2}$$

$$R_g = \frac{\frac{R_r^{'}/s}{Z_r^2} + \frac{1}{R_{fe}}}{Y_g^2} \qquad X_g = \frac{\frac{X_{\sigma r}^{'}}{Z_r^2} + \frac{1}{X_m}}{Y_g^2} \tag{68}$$

Calculate the resulting impedance seen from the terminals:

$$R = R_s + R_g \qquad X = X_{\sigma s} + X_g \qquad Z = \sqrt{R^2 + X^2} \tag{69}$$

where

s is the estimated slip;

R_s is the stator winding resistance per phase at reference temperature θ_{ref}.

6.2.6.3.4 Currents and losses

The performance values are determined in the following steps. Determine:

$I_s = \frac{U_N}{Z}$ stator phase current; $I_r^{'} = I_s \frac{1}{Y_g Z_r}$ rotor phase current;

$P_\delta = 3 I_r^{'2} \frac{R_r^{'}}{s}$ air gap power transferred to the rotor; $P_{fe} = 3 I_s^2 \frac{1}{Y_g^2 R_{fe}}$ iron loss;

$P_s = 3 I_s^2 R_s$; $P_r = 3 I_r^{'2} R_r^{'}$ stator and rotor winding loss;

$P_{LL} = P_{LL,N} \left(\frac{I_r^{'}}{I_{r,N}^{'}}\right)^2$ additional load losses,

from a value $P_{LL,N}$ at rated load, either by assigned value (method C) or measured by the reverse rotation test (method F) or by Eh-star test (method G).

The total losses are:

$$P_T = P_s + P_{fe} + P_r + P_{LL} + P_{fw} \tag{70}$$

Since input and shaft power are $P_1 = 3 I_s^2 R$ and $P_2 = P_1 - P_T$, the slip shall be corrected, and the current and loss calculations shall be repeated until P_2 for motor operation, or P_1 for generator operation, is near enough to the desired value.

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The efficiency (motor operation) results from:

$$\eta = \frac{P_2}{P_1} \quad (71)$$

7 Test methods for the determination of the efficiency of synchronous machines

7.1 Preferred testing methods

7.1.1 General

This document defines three different preferred methods with low uncertainty within the given range of application, Table 4 and Table 5. The method to be used depends on the frame size or the rating of the machine under test:

Method 2-1-2A: Direct measurement of input and output power by using a torque measuring device. To be applied for all machines with a frame size below or equal 180 mm and for permanent-magnet-excited machines of any rating.

Method 2-1-2B: Summation of separate losses with a full load test and short circuit test for the determination of the additional load losses. To be applied for all machines with a frame size above 180 mm and a rated output power up to 2 MW.

Method 2-1-2C: Summation of separate losses without a full load test. Short circuit test for the determination of the additional load losses. To be applied for all machines with a rated output power greater than 2 MW.

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Table 4 – Synchronous machines with electrical excitation: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-2A	Direct measurement: Input-output	Torque measurement	7.1.2	Machine size: $H \leq 180$	Torque measuring device for full-load
2-1-2B	Summation of losses with rated load test and short circuit test	P_{LL} from short circuit test	7.1.3	Machine size: $H > 180$ and rated output power up to 2 MW	Machine set for full-load
2-1-2C	Summation of separate losses without rated load test and P_{LL} from short circuit test	Excitation current from Potier / ASA / Swedish diagram; P_{LL} from short-circuit test	7.1.4	Rated output power greater than 2 MW	
NOTE In the table, H is the shaft height (distance from the centre line of the shaft to the bottom of the feet), in millimetres (see frame numbers in IEC 60072-1).					

Table 5 – Synchronous machines with permanent magnets: preferred testing methods

Reference	Method	Description	Subclause	Application	Required facility
2-1-2A	Direct measurement: Input-output	Torque measurement	7.1.2	All ratings	Torque measuring device for full-load

7.1.2 Method 2-1-2A – Direct measurement of input and output

7.1.2.1 General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the stator is measured in the same test.

This procedure is also applicable for synchronous machines with excitation by permanent magnets.

Input and output power are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 18);

– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

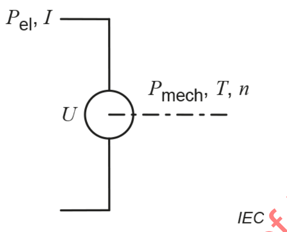

Figure 18 – Sketch for torque measurement test

For an overview, Figure 19 provides a flowchart for efficiency determination by this test method.

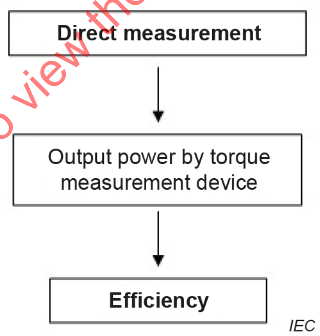

Figure 19 – Efficiency determination according to method 2-1-2A

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7.1.2.2 Test procedure

Couple either the motor under test to a load machine or the generator under test to a motor with a torque meter. Operate the machine under test at the required load.

Record U, I, P_{el}, n, T, cos φ, θ_c.

If excitation is required, proceed according to 5.9.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of permanent magnet motors, physically uncouple the motor under test, to avoid residual torque in unexcited condition induced by permanent magnets. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

7.1.2.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1 + P_{1E}} \tag{72}$$

Input power P_1 and output power P_2 are:

- in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$;
- in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

  where

  P_{mech} = $2\pi \times T \times n$.

  P_{1E} is according to 5.9.

NOTE Excitation circuit losses not supplied by P_{1E} are mechanically covered from the shaft.

7.1.3 Method 2-1-2B – Summation of separate losses with a rated load temperature test and a short circuit test

7.1.3.1 General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

- iron losses;
- windage and friction losses;
- stator and rotor copper losses;
- excitation circuit losses;
- additional load losses.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

For an overview, Figure 20 provides a flowchart for efficiency determination by this test method.

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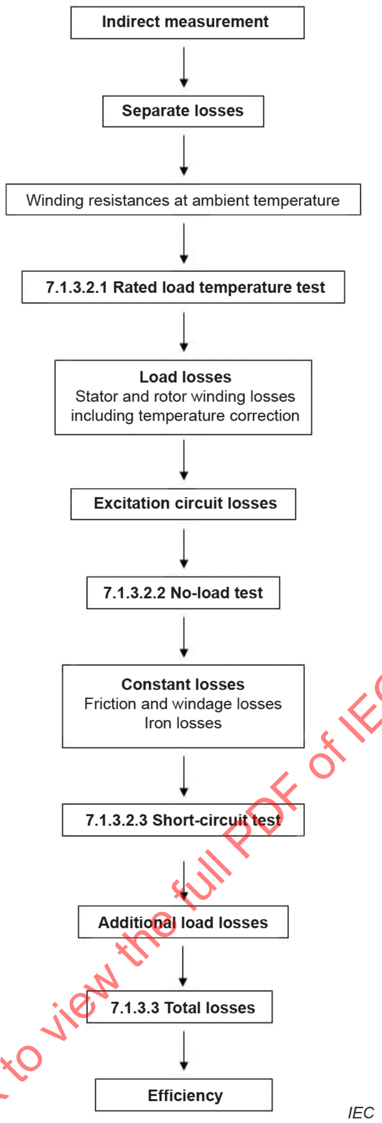

Figure 20 – Efficiency determination according to method 2-1-2B

7.1.3.2 Test procedure

7.1.3.2.1 Rated load temperature test

7.1.3.2.1.1 General

Before this load test, determine the temperature and the winding resistance of the machine with the machine at ambient temperature.

The machine shall be loaded by suitable means, with supply power according to the machine rating and operated until thermal equilibrium is achieved (rate of change of 1 K or less per half hour).

At the end of the rated-load test, record the average of at least 3 sets of test results:

– P_N, I_N, U_N, f, θ_c, θ_N;

– $R_N = R$ (the test resistance for rated load according to 5.7.1);

– θ_N (the winding temperature at rated load according to 5.7.2);

– Excitation system values according to 5.9.

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7.1.3.2.1.2 Stator winding losses

Determine the stator-winding losses:

$$P_s = 1{,}5 \times I^2 \times R_{ll} \tag{73}$$

where

R_{ll} is according to 5.7.1, corrected to 25 °C primary coolant reference temperature.

7.1.3.2.1.3 Field winding loss

The field winding loss is

$$P_f = I_f \cdot U_f \tag{74}$$

7.1.3.2.1.4 Electrical losses in brushes

In case of brushes determine brush losses from an assigned voltage drop per brush of each of the two polarities:

$$P_b = 2 \times U_b \times I_e \tag{75}$$

where

I_e is according to the load test;

U_b is the voltage drop per brush of each of the two polarities depending on brush type:

1,0 V for carbon, electrographitic or graphite;

0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

7.1.3.2.1.5 Exciter loss

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input according to the input-output method; or

b) a calibrated driving motor to measure the motor electrical power input.

Connect the exciter (in the case of a synchronous machine excited via slip-rings) to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for rated load.

Record:

– U_e, I_e, P_{1E}, n, T_E for rated load;

– $T_{E,0}$ (the torque with the exciter unexcited).

The exciter loss is:

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$$P_{Ed} = 2\pi n \left(T_E - T_{E,0} \right) + P_{1E} - P_f \quad (76)$$

When the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The total excitation loss is:

$$P_e = P_f + P_{Ed} + P_b \quad (77)$$

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7.1.3.2.2 No-load test

7.1.3.2.2.1 General

machine can be tested running as an uncoupled motor or coupled with a driving machine and operating as a generator (supplied power from shaft, measured according input-output method).

The no-load test shall be carried out on a hot machine immediately after the rated load test.

When this is not possible the test may also be carried out starting with a cold machine but the no-load losses shall be stabilized at rated frequency and voltage (by adjusting the excitation current), and unity power factor (minimum current) when running as an uncoupled motor.

In the case of a synchronous machine with shaft driven exciter (see 3.13.3.3a)), the machine should be separately excited and the exciter disconnected from its supply and from the excitation winding.

The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at a minimum number of eight values of voltage, including rated voltage, so that:

– four or more values are read approximately equally spaced between approximately 110 % and 80 % of rated voltage;

– four or more values are read approximately equally spaced between approximately 70 % and approximately 30 % of rated voltage, or (for an uncoupled running machine) to a point where the current no longer decreases.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linear with the electrical power P_0.

R_0 is $R_{II,0}$. Where resistance measurement is impracticable due to very low resistances, calculated values are permissible. The calculated values have to be based on the average value of the measured winding temperatures.

For a coupled machine, P_0 is determined from T and n.

Record excitation system values according to 5.9.

For large synchronous machines, it is recommended to record other values influencing efficiency, for example coolant temperature, gas purity, gas pressure, sliding bearings oil temperature, bearing oil viscosity.

7.1.3.2.2.2 Constant losses

For each value of voltage determine the constant losses:

$$P_c = P_0 - P_{s0} \quad (78)$$

where

$$P_{s0} = 1{,}5 \cdot I_0^2 \cdot R_{||0} \quad (79)$$

For machines with brushless exciters, excitation losses shall also be subtracted as follows:

$$P_c = P_0 - P_{s0} - P_{f,0} - P_{Ed,0} + P_{1E,0} \quad (80)$$

where

$P_{f,0}$ is the excitation winding losses at no-load;

$P_{Ed,0}$ is the exciter loss (see above) corresponding to U_e and I_e of the test point;

$P_{1E,0}$ is the power according to 5.9 corresponding to U_e and I_e of the test point.

7.1.3.2.2.3 Friction and windage losses

From the no-load test points, use all that show no significant saturation effect and develop a curve of constant losses (P_c), against the voltage squared ($U_0{}^2$). Extrapolate a straight line to zero voltage. The intercept with the zero voltage axis is the friction and windage losses P_{fw}.

Windage and friction losses are considered to be independent of load and the same windage and friction loss values may be used for each of the load points.

7.1.3.2.2.4 Iron losses

For each of the values of voltage develop a curve of constant losses against voltage. Subtract from this value the windage and friction losses to determine the iron losses.

$$P_{fe} = P_c - P_{fw} \quad (81)$$

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7.1.3.2.3 Short-circuit test

7.1.3.2.3.1 Short-circuit test with coupled machine

Couple the machine under test with its armature winding short-circuited to a drive machine, with provisions to record the torque using a torque meter (see method 2-1-2A). Operate at rated speed and excited so that the current in the short-circuited primary winding is equal to the rated current.

In the case of a machine with a shaft driven exciter (see 3.13.3.3a)), the machine should be separately excited and the exciter disconnected from its supply and from the excitation winding.

The sum of the load losses and the additional load losses is assumed to be temperature independent, and no correction to a reference temperature is made. It is assumed that the additional load losses vary as the square of the stator current.

Record: T, n, I.

Excitation system values are according to 5.9.

7.1.3.2.3.2 Short-circuit test with uncoupled machine

7.1.3.2.3.2.1 General

The machine is operated as a synchronous motor at a fixed voltage, preferably about 1/3 normal or at the lowest value for which stable operation can be obtained. The armature current is varied by control of the field current. The armature current should be varied in about six steps between 125 % and 25 % of rated current and should include one or two points at very low current. The maximum test current value, traditionally set at 125 %, should be obtained from the manufacturer since sometimes stator cooling will not permit operation in excess of 100 % rated current without damage. The highest readings should be taken first to secure more uniform stator winding temperatures during the test.

Record: P_1, I, U.

Excitation system values are according to 5.9.

NOTE For large machines, the maximum step may be limited to 60 % to 70 % of rated armature current.

7.1.3.2.3.2.2 Additional load losses

7.1.3.2.3.2.2.1 From test with coupled machine

The additional load losses at rated current result from the absorbed power of the short-circuit test with coupled machine diminished by the friction and windage losses P_{fw} and the load loss at rated current.

$$P_{LL,N} = 2\pi nT - P_{fw} - P_s \quad (82)$$

In the case of a machine with brushless excitation, the excitation winding and the exciter loss part supplied by the driving machine shall additionally be subtracted:

$$P_{LL,N} = 2\pi nT + P_{1E} - P_{fw} - P_s - P_f - P_{Ed} \quad (83)$$

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For other load points the additional load losses result from

$$P_{LL} = P_{LL,N} \times \left(\frac{I}{I_N}\right)^2 \qquad (84)$$

7.1.3.2.3.2.2.2 From test with uncoupled machine

In order to determine additional load losses at any armature current, the constant losses P_c and the armature winding loss P_s at any armature current shall be subtracted from the power input at each armature current taken in the test.

7.1.3.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \qquad (85)$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1 Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses P_T including excitation circuit losses are:

$$P_T = P_c + P_S + P_{LL} + P_e \qquad (86)$$

7.1.4 Method 2-1-2C – Summation of separate losses without a full load test

Method 2-1-2C shall be applied to machines with ratings above 2 MW. The test procedure is in principle similar to method 2-1-2B. The only difference is that the rated load temperature test is replaced by the determination of the field current by the ASA-, Swedish- or Potier-Diagram (see IEC 60034-4-1).

Apart from that the procedures for loss and efficiency determination are equivalent to method 2-1-2B.

For an overview, Figure 21 provides a flowchart for efficiency determination by this test method.

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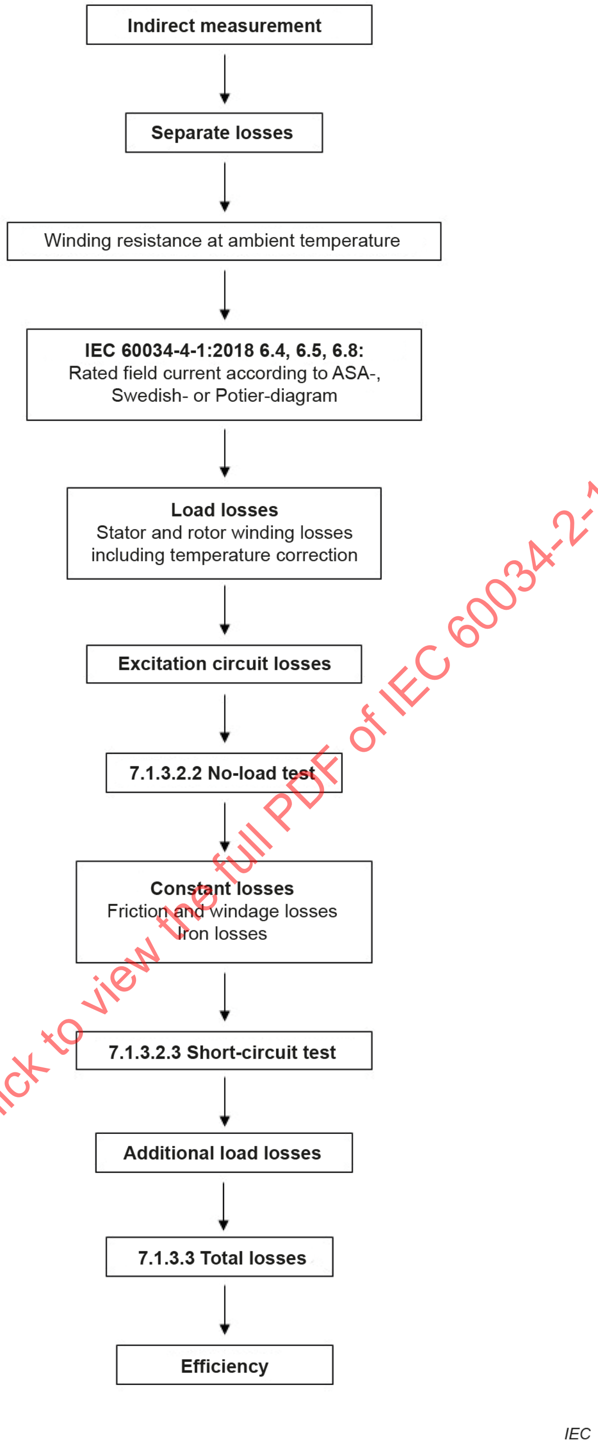

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Figure 21 – Efficiency determination according to method 2-1-2C

Prior to this test, the results of a no-load saturation test, a sustained polyphase short-circuit test and an over-excitation test at zero power factor, in accordance with 6.4, 6.5 and 6.8 of IEC 60034-4-1:2018, shall be available.

For the procedures to determine efficiency see 7.1.3, method 2-1-2B.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

7.2 Testing methods for field or routine testing

7.2.1 General

These test methods may be used for any test, i.e. field tests, customer-specific acceptance tests or routine tests.

In addition, preferred methods of Table 4 and Table 5 may also be used outside the power range identified in Table 4 and Table 5

Methods defined by this document are given in Table 6.

Table 6 – Synchronous machines: other methods

Reference	Method	Description	Subclause	Required facility
2-1-2D	Dual-supply-back-to-back	Dual-supply, back-to-back test	7.2.2	Two identical units
2-1-2E	Single-supply-back-to-back test	Single supply, back-to-back test	7.2.3	Two identical units
2-1-2F	Zero power factor with excitation current from Potier / ASA / Swedish diagram	Excitation current from Potier / ASA / Swedish diagram;	7.2.4	Supply for full voltage and current
2-1-2G	Summation of losses with load test except P_{LL}	Without consideration of P_{LL}	7.2.5	Machine set for full load

7.2.2 Method 2-1-2D – Dual supply back-to-back-test

7.2.2.1 General

For an overview, Figure 22 provides a flowchart for efficiency determination by this test method.

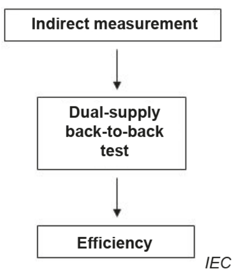

Figure 22 – Efficiency determination according to method 2-1-2D

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

7.2.2.2 Test procedure

Mechanically, couple two identical machines together (see Figure 23). Tests are made with the power supplies exchanged but with the instruments and instrument transformers remaining with the same machine.

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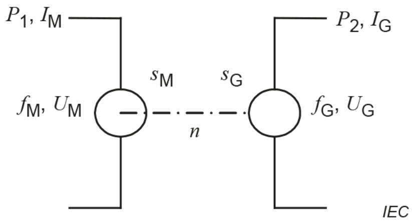

Figure 23 – Sketch for dual supply back-to-back test
($I_M = I_G$, $f_M = f_G$)

The voltage and current of the two machines shall be identical, and one machine (the motor for motor rating, the generator for generator rating) shall have the rated power factor. This can be achieved by a set of synchronous and DC machines feeding the generator output back to the line.

NOTE Power factor and excitation current of the other machine will deviate from rated values because of the losses absorbed by the two machines.

Reverse the motor and generator connections and repeat the test.

For each test, record: U, I, f, P_1, P_2, cos φ_M, cos φ_G, θ_c.

For excitation systems proceed according to 5.9.

7.2.2.3 Efficiency determination

If identical machines are run at essentially the same rated conditions, the efficiency shall be calculated from half the total losses and the average of motor input power and generator output power as follows:

$$\eta = 1 - \frac{P_T}{\frac{P_1 + P_2}{2} + P_{1E}} \quad (87)$$

where

$$P_T = \frac{1}{2}(P_1 - P_2) + P_{1E} \; ; \; P_{1E} = \frac{1}{2}\left(P_{1E,M} + P_{1E,G}\right) \quad (88)$$

P_{1E} is according to 5.9.

7.2.3 Method 2-1-2E – Single supply back-to-back-test

7.2.3.1 General

For an overview, Figure 24 provides a flowchart for efficiency determination by this test method.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

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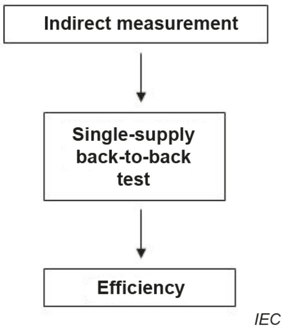

Figure 24 – Efficiency determination according to method 2-1-2E

7.2.3.2 Test procedure

Mechanically couple two identical machines together and connect them both electrically to the same power supply to operate at rated speed and rated voltage, one as a motor and the other as a generator.

NOTE Alternatively, the losses can be supplied by a calibrated driving motor.

Mechanically couple the machines with an angular displacement of their rotors enabling one machine to operate at the load conditions for which the efficiency is required, and the other machine to operate at the same absolute value of stator current (see Figure 25).

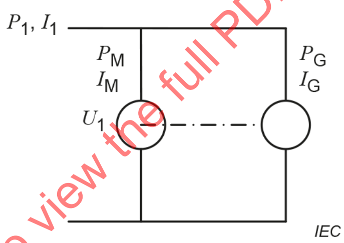

Figure 25 – Single supply back-to-back test for synchronous machines

The displacement expressed as electrical angle α for this condition is approximately the double internal electrical angle at the required load condition. In general, for a given voltage the circulating power depends on the angle α and on the excitation currents of the motor and generator. Adjust the current and power factor to rated values at one machine; the deviation in excitation current from the rated value at the other machine can be used for accuracy considerations.

For each test, record:

– U_1, I_1, P_1 of the power-frequency supply;

– I_M, P_M of the motor;

– I_G, P_G of the generator;

– excitation system values according to 5.9.

7.2.3.3 Efficiency determination

If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

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Calculate the efficiency from

$$\eta = 1 - \frac{P_T}{P_M + P_{1E}} \tag{89}$$

where

P_M is the power absorbed at the terminals of the machine acting as a motor (excluding excitation power);

P_T is the total losses, defined as half the total absorbed;

P_{1E} is the excitation power supplied by a separate source.

$$P_T = \frac{1}{2} P_1 + P_{1E}; \quad P_{1E} = \frac{1}{2}\left(P_{1E,M} + P_{1E,G}\right)$$

7.2.4 Method 2-1-2F – Zero power factor test with excitation current from Potier-, ASA- or Swedish-diagram

7.2.4.1 General

For an overview, Figure 26 provides a flowchart for efficiency determination by this test method.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

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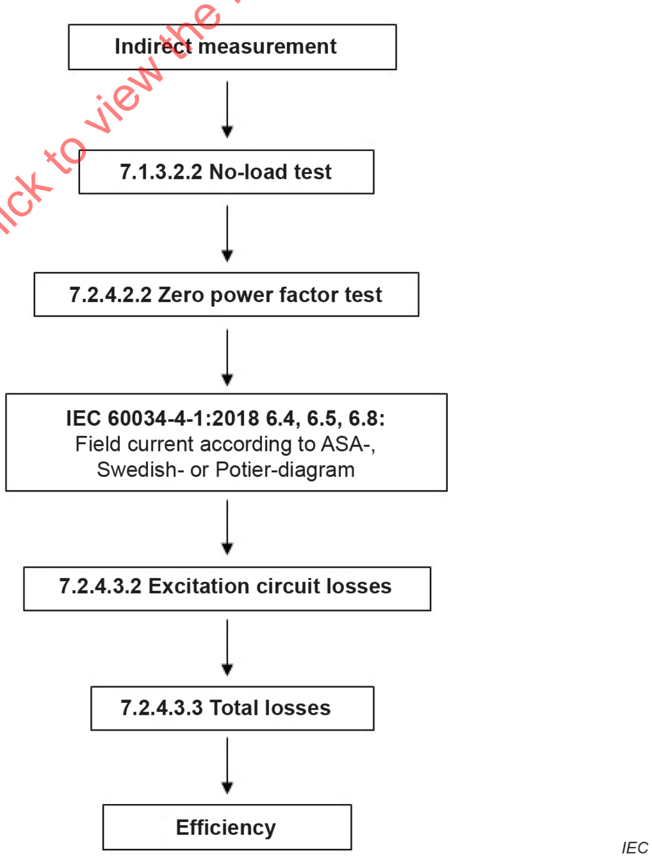

Figure 26 – Efficiency determination according to method 2-1-2F

7.2.4.2 Test procedure

7.2.4.2.1 General

Prior to this test, the results of a no-load saturation test, a sustained polyphase short-circuit test and an over-excitation test at zero power factor, in accordance with 6.4, 6.5 and 6.7 of IEC 60034-4-1:2018, shall be available.

The evaluation of the results of the no-load test shall be in accordance with 7.1.3.2.2.

7.2.4.2.2 Zero power factor test

Operate the machine uncoupled as a motor, at rated speed and over-excited. Adjust the supply voltage to the same electromotive force E and armature current I (at a power factor near zero) as at the desired load.

NOTE 1 E is the vectorial sum of terminal voltage and Potier reactance voltage drop according to 7.26.2 of IEC 60034-4-1:2018.

The test shall be made as near as possible to the stabilized operating temperature attained in operation at rated load. No winding temperature correction shall be made.

For the above test, it is necessary that the supply voltage is adjustable so that the iron losses have the same value during this test as at a rated power factor under load at rated voltage. If the supply voltage is not adjustable but is equal to the rated voltage, this could give an active iron loss appreciably different from that at full-load. In principle, reactive power should be delivered (i.e. machine over-excited), but when this is impossible due to limited exciter voltage, the test may be made with reactive power absorbed (i.e. machine under-excited) as far as stable running is possible.

The excitation winding losses at the desired load will be obtained from the excitation current estimated according to 7.26.2 of IEC 60034-4-1:2018 (Potier diagram), or 7.26.3 (ASA diagram), or 7.26.4 (Swedish diagram).

NOTE 2 The accuracy of this method depends on the accuracy of the wattmeters and the instrument transformers at low power factor.

Record at zero power factor:

- U, f, I, $P_{1,\mathrm{zpf}}$;
- excitation system values according to 5.9;
- θ_c and θ_w.

7.2.4.3 Efficiency determination

7.2.4.3.1 General

For each desired load point, determine the efficiency with the measured values as follows:

$$\eta = 1 - \frac{P_\mathrm{T}}{P_1 + P_\mathrm{1E}} \tag{90}$$

where

$P_1 = \sqrt{3} \times U_\mathrm{N} \times I \cos\varphi_\mathrm{N}$	is the power absorbed at the armature winding terminals in rated operation;
P_T	is the total losses, including excitation losses;
P_1E	is the excitation power supplied by a separate source.

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7.2.4.3.2 Excitation losses

7.2.4.3.2.1 Field winding loss

The field winding loss is

$$P_f = I_e \cdot U_f = I_e^2 \cdot R_e \quad (91)$$

applying the following temperature correction for the excitation winding resistance:

$$R_e = R_{e,0} \times \frac{235 + \theta_e}{235 + \theta_0}; \quad \theta_e = 25 + (\theta_w - \theta_c) \left(\frac{I_e}{I_{e,zpf}} \right)^2 \quad (92)$$

where

I_e is the excitation winding current determined as described in IEC 60034-4-1;

R_e is the excitation winding resistance, temperature corrected for the desired load;

$R_{e,0}$ is the cold winding resistance at temperature θ_0;

$I_{e,zpf}$ is the excitation winding current from the zero power factor test;

θ_w is the excitation winding temperature of the zpf-test;

θ_c is the reference coolant temperature of the zpf-test;

θ_e is the excitation winding temperature corrected to I_e.

7.2.4.3.2.2 Electrical losses in brushes

In case of brushes determine brush losses from an assigned voltage drop per brush of each of the two polarities:

$$P_b = 2 \times U_b \times I_e \quad (93)$$

where

I_e is the excitation winding current determined as described in IEC 60034-4-1;

U_b is the voltage drop per brush of each of the two polarities depending on brush type:

1,0 V for carbon, electrographitic or graphite;

0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

7.2.4.3.2.3 Exciter loss

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input according to the input-output method; or

b) a calibrated driving motor to measure the motor electrical power input.

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Connect the exciter (in the case of a synchronous machine excited via slip-rings) to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for rated load.

Record:

– U_e, I_e, P_{1E}, n, T_E for rated load;

– $T_{E,0}$ (the torque with the exciter unexcited).

The exciter loss is:

$$P_{Ed} = 2\pi n\left(T_E - T_{E,0}\right) + P_{1E} - P_f \quad (94)$$

If the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The total excitation loss is:

$$P_e = P_f + P_{Ed} + P_b \quad (95)$$

7.2.4.3.3 Total losses

For machines with exciter types c) and d) (see 3.13.3.3) the total losses are:

$$P_T = P_{1,zpf} + \Delta P_{fe} + P_e \quad (96)$$

where

$P_{1,zpf}$ is the absorbed power at zero power factor test;

Δp_{fe} is determined from the iron loss-voltage curve (see 7.1.3.2.2), and is the difference of the values at voltages equal to the e.m.f. for the desired load and the e.m.f. of the zero power factor test;

P_e determined as stated above.

For machines with exciters type a) and b) (see 3.13.3.3) the total losses are:

P_e, P_{ed} and P_{1E} are as defined above for the excitation winding current of the desired load, determined according to IEC 60034-4-1:

$$P_T = P_{1,zpf} + P_{1E,zpf} + \Delta P_{fe} + P_e \quad (97)$$

$$P_e = P_f + P_{Ed} - P_{f,zpf} - P_{Ed,zpf} \quad (98)$$

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where

$P_{1,\text{zpf}}$, $P_{\text{f,zpf}}$ and $P_{1\text{E,zpf}}$	are measured values from the zero power factor test;
P_{f}	is determined as for separately excited machines;
P_{Ed}, $P_{\text{Ed,zpf}}$	are determined from a test as stated above for I_{e}, R_{e} and $I_{\text{e,zpf}}$, $R_{\text{e,zpf}}$;
ΔP_{fe}	is determined from the iron loss-voltage curve (see 7.1.3.2.2), and is the difference of the values at voltages equal to the e.m.f. for the desired load and the e.m.f. of the zero power factor test.

NOTE The formulas are expressed for motor operation.

7.2.5 Method 2-1-2G – Summation of separate losses with a load test without consideration of additional load losses

The test procedure is in principle similar to method 2-1-2B. The only difference is that the additional load losses are not considered by this method, i.e. the short circuit test for their determination is skipped. This results in a significantly lower accuracy.

Apart from that, the procedures for loss and efficiency determination are equivalent to method 2-1-2B.

For an overview, Figure 27 provides a flowchart for efficiency determination by this test method.

For the procedures to determine efficiency see 7.1.3, method 2-1-2B, without consideration of the additional load loss.

This procedure is not applicable for synchronous machines with excitation by permanent magnets.

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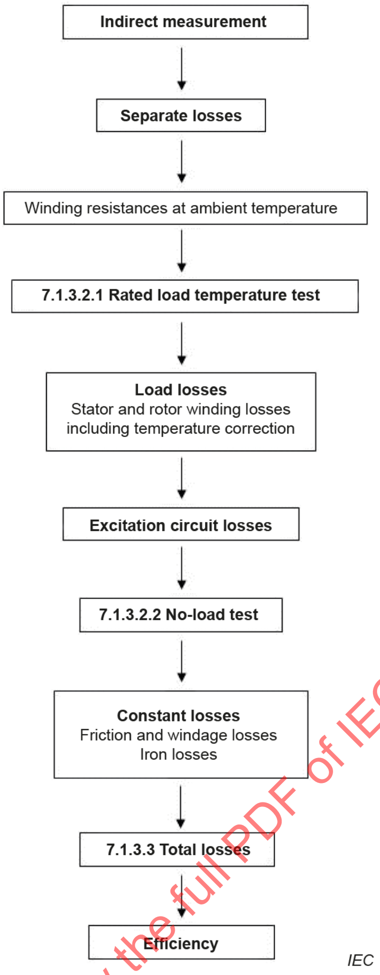

Figure 27 – Efficiency determination according to method 2-1-2G

8 Test methods for the determination of the efficiency of DC machines

8.1 Testing methods for field or routine testing

The methods shall be used for field tests, customer specific acceptance tests or routine tests.

Methods defined by this document are given in Table 7.

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Table 7 – DC machines: test methods

Reference	Method	Description	Subclause	Required facility
2-1-3A	Direct measurement: Input-output	Torque measurement	8.2	Torque measuring device for full-load
2-1-3B	Summation of losses with load test and DC component of additional load losses from test	P_{LL} DC component from single supply back-to-back test	8.3	Two identical units, booster generator, specified rectifier
2-1-3C	Summation of losses with load test and DC component of additional load losses from assigned value	P_{LL} DC component from assigned value	8.4	Specified rectifier
2-1-3D	Summation of losses without a load test	Excitation loss from an assigned ratio of load to no-load excitation current P_{LL} from assigned value	8.5	
2-1-3E	Single-supply-back-to-back test	Single supply, back-to-back test	8.6	Two identical units Booster generator

8.2 Method 2-1-3A – Direct measurement of input and output

8.2.1 General

This is a test method in which the mechanical power P_{mech} of a machine is determined by measurement of the shaft torque and speed. The electrical power P_{el} of the armature is measured in the same test.

Input and output power are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$ (see Figure 28);

– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$.

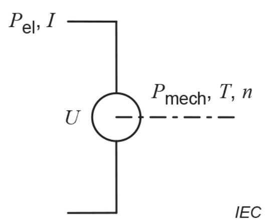

Figure 28 – Sketch for torque measurement test

For an overview, Figure 29 provides a flowchart for efficiency determination by this test method.

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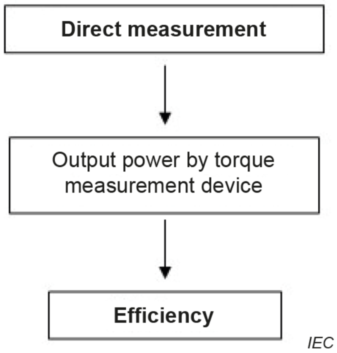

Figure 29 – Efficiency determination according to method 2-1-3A

8.2.2 Test procedure

Couple either the motor under test to a load machine or the generator under test to a motor with a torque meter. Operate the machine under test at the required load.

Record U, I, P_{el}, n, T, θ_c.

If excitation is required, proceed according to 5.9.

Immediately after the test, the drift of the torque measuring device shall be checked. In case of a deviation above the allowed tolerance of the torque measuring device, adjust it and repeat the measurements.

8.2.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_2}{P_1 + P_{1E}} \quad (99)$$

Input power P_1 and output power P_2 are:

– in motor operation: $P_1 = P_{el}$; $P_2 = P_{mech}$;

– in generator operation: $P_1 = P_{mech}$; $P_2 = P_{el}$;

where

P_{mech} = 2π × T × n;

P_{1E} is according to 5.9.

NOTE Excitation circuit losses not supplied by P_{1E} are mechanically covered from the shaft.

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8.3 Method 2-1-3B – Summation of losses with a load test and DC component of additional load losses from test

8.3.1 General

This is a test method in which the efficiency is determined by the summation of separate losses. The respective loss components are:

- iron losses;
- windage and friction losses;
- armature winding and brush losses;
- excitation circuit and exciter losses;
- additional load losses.

For an overview, Figure 30 provides a flowchart for efficiency determination by this test method.

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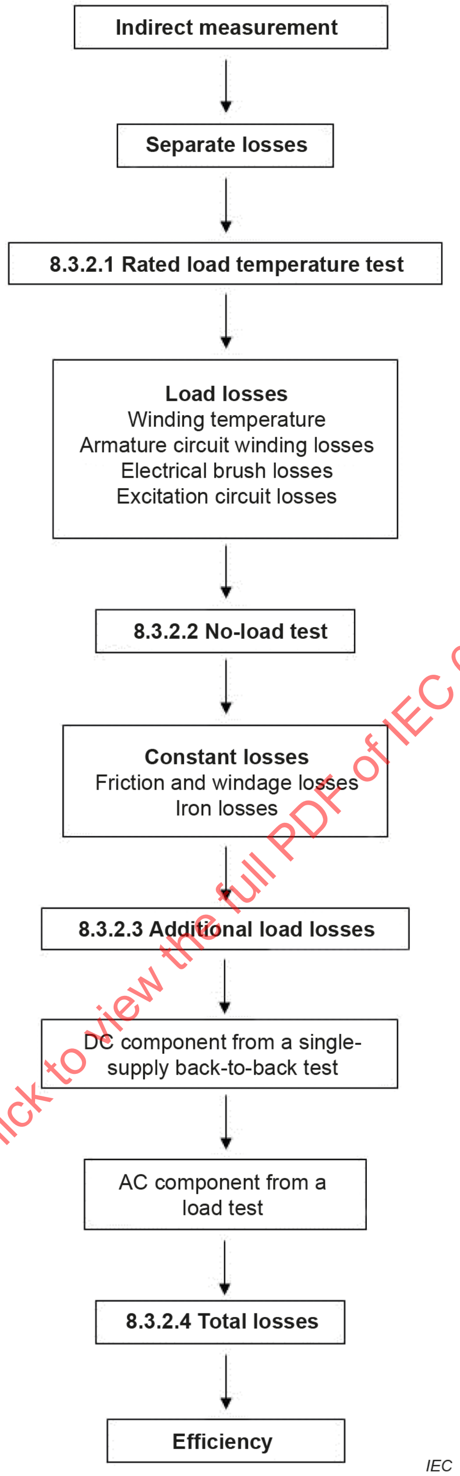

Figure 30 – Efficiency determination according to method 2-1-3B

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8.3.2 Test procedure

8.3.2.1 Rated load temperature test

8.3.2.1.1 General

Before this load test, determine the ambient temperature and the winding resistance of the motor.

The machine shall be loaded by suitable means, with supply power according to the machine rating and operated until thermal equilibrium is achieved (rate of change of 1 K or less per half hour).

At the end of the rated-load test, record the average of at least 3 sets of test results:

– P_N, I_N, U_N, θ_c, θ_N;
– $R_N = R$ (the test resistance for rated load according to 5.7.1);
– θ_N (the winding temperature at rated load according to 5.7.2);
– excitation system values according to 5.9.

In the case of DC machines on rectified power, the mean value I_{av} and the RMS value I shall be measured.

For DC machines, R is the total resistance of all windings carrying armature current (armature, commutating, compensating winding, compound winding). Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

8.3.2.1.2 Armature circuit winding losses

For each load recorded determine the armature-circuit-windings losses:

$$P_a = I^2 \times R \tag{100}$$

R according to 5.7.2 with R taking all windings in the armature circuit into account.

8.3.2.1.3 Electrical brush losses

Determine brush losses using an assigned voltage drop per brush:

$$P_b = 2 \times U_b \times I \tag{101}$$

where

I is the armature current at the rating considered;

U_b is the assumed voltage drop per brush depending on brush type:

1,0 V for carbon, electrographitic or graphite;

0,3 V for metal-carbon.

The given values for the voltage drop per brush (1 V or 0,3 V) may be used if no specific information is available.

8.3.2.1.4 Excitation circuit losses

The excitation winding losses result from the measured voltage and current as follows:

$$P_f = U_e \times I_e \tag{102}$$

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8.3.2.1.5 Exciter losses

Uncouple the exciter from the main machine (if possible), then couple the exciter to:

a) a torque measuring device to determine the mechanical power input;

b) a calibrated driving motor to measure the motor electrical power input.

Connect the exciter to a suitable resistive load. Operate the exciter unexcited and with voltage U_e and current I_e for each of the load points.

Record:

– U_e, I_e, P_{Ed}, n, T_E for each load point (P_{Ed} according to 3.13.3.3);

– $T_{E,0}$ (the torque with the exciter unexcited).

If the exciter cannot be uncoupled from the machine, the exciter losses shall be provided by the manufacturer.

The exciter losses P_{Ed} are

$$P_{Ed} = \left(T_E - T_{E,0}\right) \times 2\pi n + P_{1E} - U_e \times I_e \tag{103}$$

where $T_{E,0}$ is the torque with the exciter unexcited.

If testing is not practical, calculated losses shall be used.

8.3.2.2 No-load test

8.3.2.2.1 General

The machine can be tested running as an uncoupled motor or coupled with a driving machine and operating as a generator (supplied power from torque, measured according input-output method).

The no-load test shall be carried out on a hot machine immediately after the rated load test.

If this is not possible the test may also be carried out starting with a cold machine but the no-load losses shall be stabilized. The no-load losses are considered stabilized when the no-load power input varies by 3 % or less, when measured at two successive 30 min intervals.

Test at a minimum number of eight values of voltage, including rated voltage, so that:

– four or more values are read approximately equally spaced between 110 % and 80 % of rated voltage;

– four or more values are read approximately equally spaced between 70 % and approximately 30 % of rated voltage, or (for an uncoupled running machine) to a point where the current no longer decreases.

For uncoupled DC machines, the speed shall be maintained constant by adjusting the field current.

The test shall be carried out as quickly as possible with the readings taken in descending order of voltage.

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Record at each of the voltage values: U_0, I_0, P_0.

Determine the resistance R_0 immediately before and after the no-load test.

The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linear with the electrical power P_0.

Where resistance measurement is impracticable due to very low resistances, calculated values are permissible.

For a coupled machine, P_0 is determined from T and n.

8.3.2.2.2 Constant losses

Determine the constant losses from the following formula:

$$P_c = P_0 - P_a \tag{104}$$

where

$$P_a = I_0^2 \times R_0 \tag{105}$$

I_0 and R_0 are recorded for each value of voltage.

If resistance measurement is impracticable due to very low resistances, calculated values are permissible, corrected to the expected winding temperature.

NOTE In the armature losses P_a, the following are included: compensating windings, commutating pole windings and shunt resistors (diverters). In the case of diverters in parallel with a series winding, the electrical winding losses may be determined using the total current and the resulting resistance.

8.3.2.2.3 Friction and windage losses (optional)

For each of the values of voltage 70 % or less develop a curve of constant losses (P_c) against voltage U_0^2. Extrapolate a straight line to zero voltage. The intercept with the zero voltage axis is the windage and friction losses P_{fw}.

8.3.2.2.4 Iron losses (optional)

For each of the values of voltage between 80 % and 110 % develop a curve of constant losses (P_c) against voltage U_0. The iron loss shall be taken for the inner voltage U_i, at:

$$U_i = U_N - (IR)_a - 2U_b \text{ in the case of a motor} \tag{106}$$

$$U_i = U_N + (IR)_a + 2U_b \text{ in the case of a generator} \tag{107}$$

where

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U_N is the rated voltage;

$2U_b$ is the brush voltage-drop as given at the load test;

I is the current of the desired load point;

R is the resistance of all windings of the armature circuit at full-load temperature.

Determine the iron loss from

$$P_{fe} = P_c - P_{fw} \tag{108}$$

8.3.2.3 Additional load losses

8.3.2.3.1 DC losses from single supply back-to-back-test

This method allows the determination of the DC component of the additional load losses if two identical DC machines are available. They shall be coupled and electrically connected together and supplied by a DC source, the machine acting as a generator with a booster generator in series (see Figure 31).

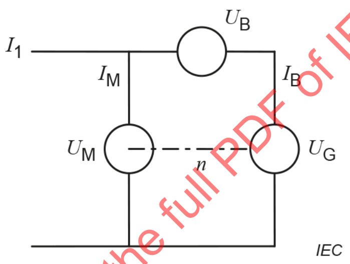

Figure 31 – Sketch for single supply back-to-back test for determination of DC component of additional load losses

If the machines are designed for motor operation, the supply shall deliver rated voltage and rated current to the machine acting as motor. In the case of machines designed for generator operation, the supply voltage shall be adjusted to rated voltage and rated current at the machine acting as generator. The motor and the generator shall be operated with the flux required to produce the e.m.f. corresponding to the test load.

NOTE The voltage supply mainly covers the no-load losses, the booster mainly covers the load losses.

In the case of machines with shaft driven exciters, the excitation windings shall be separately excited for this test, with the exciters disconnected from their supply and the excitation winding.

When temperatures have stabilized, record: U, I, U_B, I_B, $U_{e,M}$, $I_{e,M}$, $U_{e,G}$, $I_{e,G}$, n, θ_c.

The DC component of the additional load loss is

$$P_{LL} = \frac{1}{2}\left(P_1 - \sum P_c - \sum P_a - P_{con} - 2U_b(I + I_B) - 2I_B U_b\right) \tag{109}$$

where

$P_1 = U_M \times I_1 + U_B \times I_B$ is the power from supply and booster; see Figure 31;

ΣP_c is the sum of constant losses of both machines;

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ΣP_a is the sum of the resistance losses of both armature circuits;

P_{con} is the loss in cable connections.

For determination of losses for other load points, apply the factors as described in Table 8.

8.3.2.3.2 AC losses (converter-fed DC machines)

For motors supplied by static power converters, whenever the current ripple factor (see IEC 60034-1) of the armature current exceeds 0,1, the additional losses caused by the AC component of the armature current shall be considered in addition to the losses specified above.

The losses are obtained from a load test with the machine supplied by an appropriate rectifier. See also IEC 60034-19.

Record:

- P_1 the AC power supplied to the machine;
- I the AC r.m.s. current component; and
- θ_w the temperatures of the windings in galvanic contact with the armature circuit.

NOTE For series-wound motors, a small amount of the AC power input contributes to the developed motor torque. This amount is usually so small that it can be neglected.

The additional losses due to the AC part of the supply voltage result from:

$$P_{LL} = P_1 - I^2 \times R \tag{110}$$

where R is the DC resistance of the armature circuit at rated load temperatures according to 5.7.2.

8.3.2.4 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \tag{111}$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1 Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses shall be taken as the sum of the separate losses consisting of

$$P_T = P_c + P_a + P_b + P_{LL} + P_e \tag{112}$$

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$$P_e = P_f + P_{Ed} \tag{113}$$

where

P_a is the armature-winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional load losses;

P_f is the excitation (field winding) loss;

P_{Ed} is the exciter loss.

8.4 Method 2-1-3C – Summation of losses with a load test and DC component of additional load losses from assigned value

8.4.1 General

As method 2-1-3B, this test method determines efficiency by the summation of separate losses. But in this case the DC component of the additional load losses is derived from an assigned value.

For an overview, Figure 32 provides a flowchart for efficiency determination by this test method.

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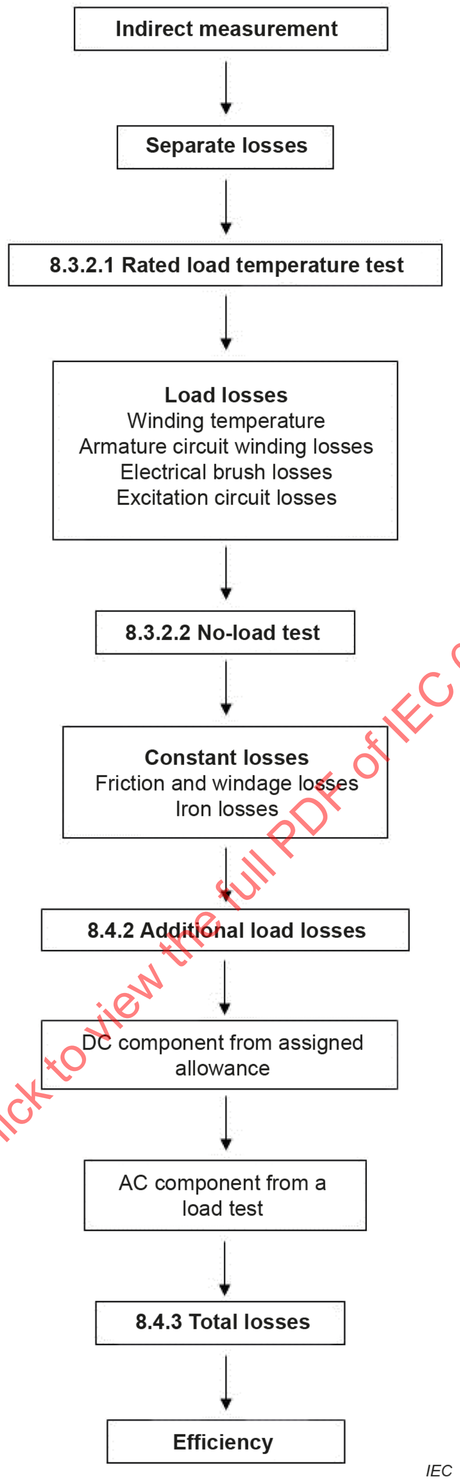

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Figure 32 – Efficiency determination according to method 2-1-3C

8.4.2 Test procedure

8.4.2.1 General

Apart from the determination of the DC component of the additional load losses, the same procedures as in 8.3.2 shall be applied.

8.4.2.2 DC component of the additional load losses from assigned allowance

It is assumed that the DC losses vary as the square of the current, and that their total value at maximum rated current is:

a) for uncompensated machines:
   – 1 % of the rated input power for motors;
   – 1 % of the rated output power for generators;

b) for compensated machines:
   – 0,5 % of the rated input power for motors;
   – 0,5 % of the rated output power for generators.

For constant speed machines, the rated power is the power with maximum rated current and maximum rated voltage.

For variable speed motors where the speed change is obtained by applied voltage, the rated input power is defined at each speed as being the input power when the maximum rated current is associated with the applied voltage of the particular speed considered.

For variable speed motors where the increase in speed is obtained by weakening the field, the rated input power is defined as being the input power when the rated voltage is associated with the maximum rated current. For variable speed generators where the voltage is maintained constant by varying the field, the rated output power is defined as being the output power, which is available at the terminals at rated voltage and maximum rated current. The allowances for additional losses at the speed corresponding to the full field shall be as specified above under a) and b). The allowances for additional losses at other speeds shall be calculated using the appropriate multiplying factors given in Table 8.

Table 8 – Multiplying factors for different speed ratios

Speed ratio	Factor
1,5:1	1,4
2:1	1,7
3:1	2,5
4:1	3,2

The speed ratio in the first column of Table 8 shall be taken as the ratio of actual speed under consideration to the minimum rated speed for continuous running.

For speed ratios other than those given in Table 8, the appropriate multiplying factors may be obtained by interpolation.

8.4.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \tag{114}$$

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where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1 Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses shall be taken as the sum of the separate losses consisting of

$$P_T = P_c + P_a + P_b + P_{LL} + P_e \tag{115}$$

$$P_e = P_f + P_{Ed} \tag{116}$$

where

P_a is the armature winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional losses;

P_f is the excitation (field winding) loss;

P_{Ed} is the exciter loss.

8.5 Method 2-1-3D – Summation of losses without a load test

8.5.1 General

As method 2-1-3C, this test method determines efficiency by the summation of separate losses. But in this case, the armature circuit winding losses and the excitation circuit losses are not determined by a load test, but by calculation.

For an overview, Figure 33 provides a flowchart for efficiency determination by this test method.

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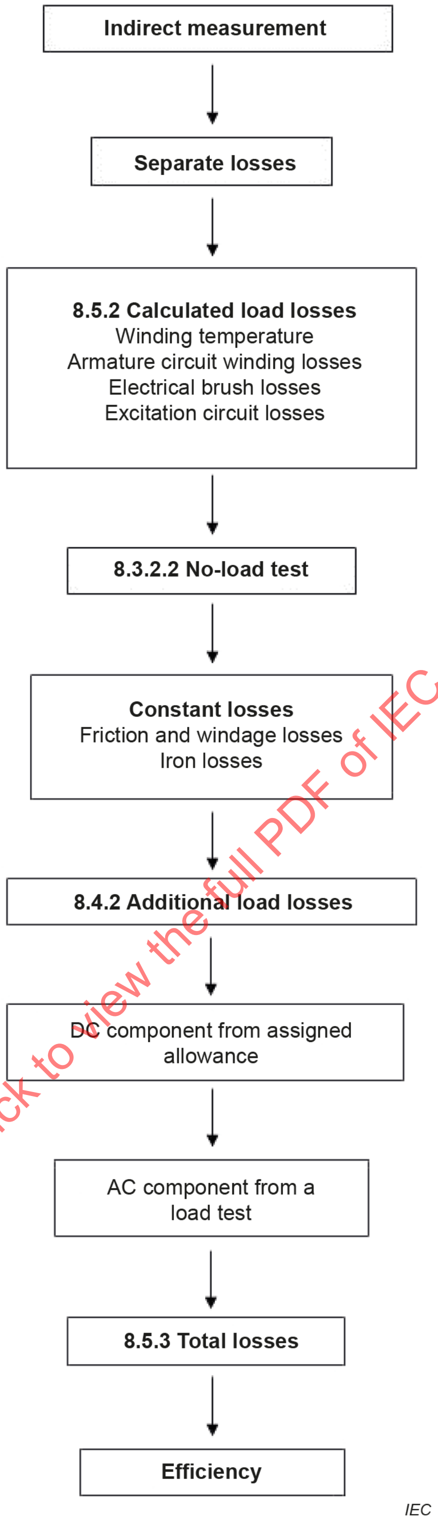

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Figure 33 – Efficiency determination according to method 2-1-3D

8.5.2 Test procedure

8.5.2.1 General

Apart from the determination of the excitation circuit losses, the same procedures as in 8.4.2 shall be applied.

8.5.2.2 Excitation circuit losses

Without a load test, the excitation winding losses P_e shall be calculated from $I_e^2 \times R_f$, where R_f is the resistance of the shunt excitation winding (or separately excited winding), corrected to the reference temperature specified in 5.7.3 and I_e is the excitation current according to the following list.

a) For shunt connected or separately excited generators with or without commutating poles, I_e is 110 % of the excitation current corresponding to no-load at a voltage equal to the rated voltage plus ohmic drop in the armature circuit (armature, brushes and commutating windings if any) at the current of the specific load point.

b) For compensated shunt or separately excited generators, I_e is the excitation current corresponding to no-load at a voltage equal to the rated voltage plus ohmic drop in the armature circuit at the current of the specific load point.

c) For level-compounded generators, I_e is the excitation current for the rated no-load voltage.

d) For over-compounded and under-compounded generators, and special types of generator not covered by items a) to c), I_e is subject to agreement.

e) For shunt wound motors, I_e is equal to no-load excitation current corresponding to the rated voltage.

8.5.3 Efficiency determination

The efficiency is:

$$\eta = \frac{P_1 + P_{1E} - P_T}{P_1 + P_{1E}} = \frac{P_2}{P_2 + P_T} \tag{117}$$

where

P_1 is the input power excluding excitation power from a separate source;

P_2 is the output power;

P_{1E} is the excitation power supplied by a separate source.

NOTE 1 Usually, the first expression is preferred for a motor, the second for a generator.

NOTE 2 P_T includes the excitation power P_e (see 5.9) of the machine where applicable.

The total losses shall be taken as the sum of the separate losses consisting of

$$P_T = P_c + P_a + P_b + P_{LL} + P_e \tag{118}$$

$$P_e = P_f + P_{Ed} \tag{119}$$

where

P_a is the armature winding loss;

P_b is the brush loss;

P_c is the constant losses;

P_{LL} is the additional losses;

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P_e is the excitation circuit losses;

P_f is the calculated excitation (field winding) loss;

P_{Ed} is the exciter loss.

8.6 Method 2-1-3E – Single supply back-to-back test

8.6.1 General

For an overview, Figure 34 provides a flowchart for efficiency determination by this test method.

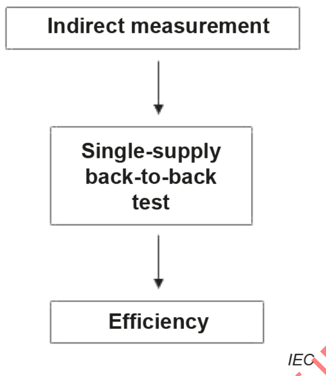

Figure 34 – Efficiency determination according to method 2-1-3E

8.6.2 Test procedure

Mechanically couple two identical machines together and connect them both electrically to the same power supply so as to operate at rated speed and rated voltage, one as a motor and the other as a generator.

NOTE Alternatively, the losses can be supplied either by a calibrated driving motor, a booster, or otherwise by a combination of these various means.

Connect the driven machine to the supply with a booster generator in series (see Figure 35). Operate both machines at approximately the current and the internal voltage corresponding to the load point for which the efficiency is required. For motors, the supply shall deliver rated voltage and the required load to the motor. For generators, the voltage has to be adjusted by the booster for rated voltage and the required load at the generator. The voltage supply mainly covers the no-load losses, the booster covers the load losses.

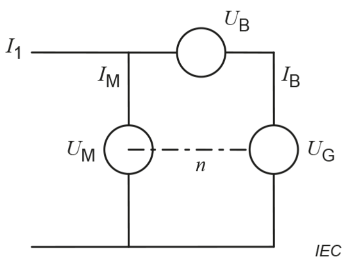

Figure 35 – Sketch for single supply back-to-back test

If no booster is available, the common terminal voltage should be adjusted so that the mean value of the currents of both machines is the rated current.

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For each test, record:

– U_M, I_1 of the power supply;

– P_M absorbed at the motor terminals;

– U_B, I_B of the booster;

– n, θ_c.

For excitation systems, proceed according to 5.9.

8.6.3 Efficiency determination

If identical machines are run at essentially rated conditions, the efficiency is calculated by assigning half the total losses to each machine.

Calculate the efficiency from

$$\eta = 1 - \frac{P_T}{P_M + P_{1E}} \qquad (120)$$

where

P_M is the power absorbed at the terminals of the machine acting as a motor (excluding excitation power);

P_T is the total losses, defined as half the total absorbed;

P_{1E} is the excitation power supplied by a separate source;

$$P_T = \frac{1}{2}\left(U_M \times I_1 + U_B \times I_B\right) + P_{1E} \;; \qquad P_{1E} = \frac{1}{2}\left(P_{1E,M} + P_{1E,G}\right) \qquad (121)$$

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Annex A
(normative)

Calculation of values for the Eh-star method

Determine the following complex voltages and currents from the test results:

$$\begin{aligned} \underline{U}_{UV} &= U_{UV} \\ U'_{WU} &= \frac{U_{VW}^2 - U_{WU}^2 - U_{UV}^2}{2 \cdot U_{UV}} \\ U''_{WU} &= \sqrt{U_{WU}^2 - U'^2_{WU}} \\ U'_{VW} &= -U_{UV} - U'_{WU} \\ U''_{VW} &= -U''_{WU} \\ I'_V &= -\frac{(P_{UV} - P_{VW}) + U_{WU} \cdot I_W}{U_{UV}} \end{aligned} \tag{A.1}$$

In the above formula, it is assumed that current I_W is in phase with voltage U_{WU}. In the case where the impedance of the resistor contains a noticeable reactive component, use the following formula

$$I'_V = -\frac{(P_{UV} - P_{VW}) + R_{eh} \cdot I_W^2}{U_{UV}}$$

where R_{eh} is the measured value of the resistive component.

$$\begin{aligned} I''_V &= \sqrt{I_V^2 - I'^2_V} \\ k_1 &= \frac{1}{2 \cdot I_V^2} \cdot \left(I_W^2 - I_U^2 - I_V^2 \right) \\ I'_U &= k_1 \cdot I'_V + \sqrt{(k_1^2 - \frac{I_U^2}{I_V^2})(I'^2_V - I_V^2)} \\ I''_U &= \frac{k_1 I_V^2 - I'_U \cdot I'_V}{I''_V} \\ I'_W &= -I'_U - I'_V \\ I''_W &= -I''_U - I''_V \end{aligned} \tag{A.2}$$

Determine the inner line-to-line voltages from the complex line-to-line voltages and currents:

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$$\underline{U}_{\text{iUV}} = \underline{U}_{\text{UV}} + \frac{R_{\text{VW}}}{2} \cdot \left(\underline{I}_{\text{V}} - \underline{I}_{\text{U}}\right)$$
$$\underline{U}_{\text{iVW}} = \underline{U}_{\text{VW}} + \frac{R_{\text{VW}}}{2} \cdot \left(\underline{I}_{\text{W}} - \underline{I}_{\text{V}}\right) \quad \text{(A.3)}$$
$$\underline{U}_{\text{iWU}} = \underline{U}_{\text{WU}} + \frac{R_{\text{VW}}}{2} \cdot \left(\underline{I}_{\text{U}} - \underline{I}_{\text{W}}\right)$$

Separate into positive and negative sequence line-to-line components ($\underline{a} = e^{j2\pi/3}$):

$$\underline{U}_{\text{iLL(1)}} = \frac{1}{3} \cdot \left(\underline{U}_{\text{iUV}} + \underline{a} \cdot \underline{U}_{\text{iVW}} + \underline{a}^2 \cdot \underline{U}_{\text{iWU}}\right)$$
$$\underline{U}_{\text{iLL(2)}} = \frac{1}{3} \cdot \left(\underline{U}_{\text{iUV}} + \underline{a}^2 \cdot \underline{U}_{\text{iVW}} + \underline{a} \cdot \underline{U}_{\text{iWU}}\right) \quad \text{(A.4)}$$

Determine the positive and negative sequence components of the inner phase voltage $\underline{U}_{\text{i}}$:

$$\underline{U}_{\text{i(1)}} = \frac{1}{\sqrt{3}} \cdot e^{-j\frac{\pi}{6}} \cdot \underline{U}_{\text{iLL(1)}}$$
$$\underline{U}_{\text{i(2)}} = \frac{1}{\sqrt{3}} \cdot e^{j\frac{\pi}{6}} \cdot \underline{U}_{\text{iLL(2)}} \quad \text{(A.5)}$$

Determine the asymmetrical inner phase voltages:

$$\underline{U}_{\text{iU}} = \underline{U}_{\text{i(1)}} + \underline{U}_{\text{i(2)}}$$
$$\underline{U}_{\text{iV}} = \underline{a}^2 \cdot \underline{U}_{\text{i(1)}} + \underline{a} \cdot \underline{U}_{\text{i(2)}} \quad \text{(A.6)}$$
$$\underline{U}_{\text{iW}} = \underline{a} \cdot \underline{U}_{\text{i(1)}} + \underline{a}^2 \cdot \underline{U}_{\text{i(2)}}$$

Determine the iron loss resistance:

$$R_{\text{fe}} = \frac{U_{\text{t}}^2}{P_{\text{fe}}} \quad \text{(A.7)}$$

where

U_{t} is according to 6.2.5.2;

P_{fe} is according to 6.1.3.2.5.

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$$\underline{I}_{\text{feU}} = \frac{\underline{U}_{\text{iU}}}{R_{\text{fe}}}$$
$$\underline{I}_{\text{feV}} = \frac{\underline{U}_{\text{iV}}}{R_{\text{fe}}} \qquad \text{(A.8)}$$
$$\underline{I}_{\text{feW}} = \frac{\underline{U}_{\text{iW}}}{R_{\text{fe}}}$$

Determine the inner phase currents:

$$\underline{I}_{\text{iU}} = \underline{I}_{\text{U}} - \underline{I}_{\text{feU}}$$
$$\underline{I}_{\text{iV}} = \underline{I}_{\text{V}} - \underline{I}_{\text{feV}} \qquad \text{(A.9)}$$
$$\underline{I}_{\text{iW}} = \underline{I}_{\text{W}} - \underline{I}_{\text{feW}}$$

Determine the positive and negative sequence components of the inner phase currents:

$$\underline{I}_{\text{i(1)}} = \frac{1}{3} \cdot \left(\underline{I}_{\text{iU}} + \underline{a} \cdot \underline{I}_{\text{iV}} + \underline{a}^2 \cdot \underline{I}_{\text{iW}} \right)$$
$$\underline{I}_{\text{i(2)}} = \frac{1}{3} \cdot \left(\underline{I}_{\text{iU}} + \underline{a}^2 \cdot \underline{I}_{\text{iV}} + \underline{a} \cdot \underline{I}_{\text{iW}} \right) \qquad \text{(A.10)}$$

The absolute values of the positive sequence current $I_{\text{i(1)}}$ shall be less than 30 % of the absolute value of the negative sequence current $I_{\text{i(2)}}$ in order to achieve accurate results. If this condition is not met, the test shall be repeated using a different value of R_{eh}.

Determine the air-gap power:

$$P_{\delta(1)} = 3 \cdot \left(U_{i(1)}^{'} \cdot I_{i(1)}^{'} + U_{i(1)}^{''} \cdot I_{i(1)}^{''} \right)$$
$$P_{\delta(2)} = 3 \cdot \left(U_{i(2)}^{'} \cdot I_{i(2)}^{'} + U_{i(2)}^{''} \cdot I_{i(2)}^{''} \right) \qquad \text{(A.11)}$$

Determine the additional load losses:

$$P_{\text{Lr}} = k \cdot \left[(1 - s) \cdot \left(P_{\delta(1)} - P_{\delta(2)} \right) - P_{\text{fw}} \right]$$

$$\text{where} \quad k = \frac{1}{1 + \left(I_{\text{i(1)}} / I_{\text{i(2)}} \right)^2} \qquad \text{(A.12)}$$

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Annex B
(informative)

Types of excitation systems

The types of excitation systems considered for determination of the exciter losses are:

a) shaft driven exciter

A DC or AC exciter machine is driven by the shaft of the main unit, directly or through a gear. If the main unit is a synchronous machine the excitation power is supplied to the excitation winding via slip-ring and brushes.

b) brushless exciter

An AC exciter coupled to a synchronous main unit supplies the field winding directly via rotating rectifiers, avoiding slip-rings and brushes. The exciter can be a synchronous generator or an induction machine.

Excitation power of a synchronous exciter is derived either from a directly coupled AC pilot exciter with permanent magnet excitation, or from an auxiliary (secondary) winding in the main unit stator slots (same as in e)), or from a static supply.

An induction exciter is connected to a variable AC voltage supply.

c) separate rotating exciter

A DC or AC generator as part of a separate motor generator set supplies the excitation current to the field winding of the main unit.

d) static excitation system (static exciter)

The excitation power is supplied to the field winding of the main unit by a static source such as batteries or a static power converter-fed from a separate source.

e) excitation from auxiliary winding (auxiliary winding exciter)

The excitation power for an AC generator is provided by an auxiliary (secondary) winding in the main unit stator slots, utilizing fundamental or harmonic flux, and supplied to the field winding via rectifiers, slip-rings and brushes.

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Annex C
(informative)

Induction machine slip measurement

Rotor losses in induction machines are directly proportional to slip, with slip defined as the fractional departure of shaft speed from the synchronous speed corresponding to the supply frequency and the number of motor poles.

Slip measurements should be ratio-metric, i.e. concurrently account for both motor shaft speed and the frequency of the supply to the motor during the time interval over which those measurements are made. An example is the stroboscopic method, which uses supply-frequency-derived pulsed illumination of an induction motor shaft, and counts the number of slip revolutions over a known time period.

The following method is based on that principle, and provides very high accuracy slip measurements which can be automatically transferred to a data acquisition system.

Figure C.1 shows the principle of the measurement system, in which two pulse trains are generated: one derived directly from the shaft of an induction machine under test, and a second directly related to the frequency of the power supply. The diagram shows two sequential shaft encoders, each of which produce the same number of output pulses per revolution, connected to the shafts of an induction machine under test and a small synchronous motor connected to the same power supply, respectively.

The reference synchronous machine may be regarded as having zero slip.

The two pulse trains are fed to the inputs of a two-channel digital counter which has the facility to calculate and display the ratio of the two input frequencies.

If a motor-alternator set is used as the power supply for induction machine testing and measurements, then the second (reference) shaft encoder may be connected directly to the alternator shaft. A further possibility is that the reference frequency be generated electronically, using a phase-locked loop system.

If the ratio produced by the dual-channel counter, as above, is multiplied by the nominal synchronous speed of the reference (synchronous) motor in Figure C.1 (e.g. 1 500 min^{-1} for a 4 pole synchronous motor with a nominal supply frequency of 50 Hz), then the counter, configured as above, displays the shaft speed of the induction machine under test corrected for supply frequency, regardless of the induction machine pole number.

Slip may then be calculated directly from that indicated shaft speed.

If the two counters are started and stopped synchronously (i.e. at exactly the same times), the actual counting time is not critical. Slip measurement should be made over the same averaging time as the other measurements of motor voltage, current, electrical power and torque.

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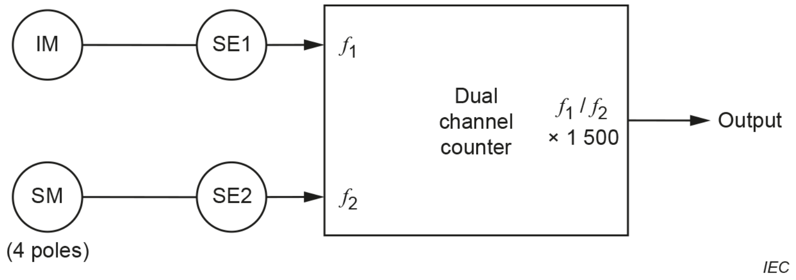

Key

IM	Induction machine under test (any number of poles)
SM	Small synchronous motor (e.g. 4 poles) or main laboratory M-G set
SE1	Sequential shaft encoder, with e.g. 600 pulses per revolution (p.p.r.)
SE2	Sequential shaft encoder, with same no. of p.p.r. as SE1
f_1	Frequency of pulse train from SE1
f_2	Frequency of pulse train from SE2
Output	ratio f_1/f_2 × synchronous speed of SM

Figure C.1 – Slip measurement system block diagram

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Annex D
(informative)

Test report template for method 2-1-1B

Manufacturer Logo	

Date of test:		Report number:		Date of issue:	

Motor description						
Rated output power	kW			Manufacturer		
Rated voltage	V			Model Nr.		
Rated current	A			Serial Nr.		
Rated speed	min^{-1}			Duty type acc. to IEC 60034-1		
Supply frequency	Hz			Design		
Number of phases	-			Insulation class acc. to IEC 60085		
IEC 60034-30-1 (rated)	IE-Code			Max. ambient temperature	°C	

Initial motor conditions			
Test resistance	R_i	Ω	
Winding temperature	θ_i	°C	
Ambient temperature	θ_a	°C	

6.1.3.2.1 Rated load test			
Test resistance	R_N	Ω	
Winding temperature	θ_N	°C	
Ambient temperature	θ_a	°C	

6.1.3.2.3 Load curve test			Test resistance before load test			R	Ω	
Rated output power		%	**125%**	**115%**	**100%**	**75%**	**50%**	**25%**
Torque	T	N.m						
Input power	P_1	W						
Line current	I	A						
Operating speed	n	min^{-1}						
Teminal voltage	U	V						
Frequency	f	Hz						
Winding temperature	θ_L	°C						
			Test resistance after load test			R	Ω	

6.1.3.2.4 No-load test					Test resistance before no-load test			R	Ω	
Rated voltage		%	**110%**	**100%**	**95%**	**90%**	**60%**	**50%**	**40%**	**30%**
Input power	P_0	W								
Line current	I_0	A								
Terminal voltage	U_0	V								
Frequency	f_0	Hz								
W. temperature	θ_0	°C								
					Test resistance after no-load test			R	Ω	

6.1.3.3 Efficiency determination								
Rated output power corr.	$P_{2,\theta}$	%	**125%**	**115%**	**100%**	**75%**	**50%**	**25%**
Output power corrected	$P_{2,\theta}$	W						
Slip corrected	$s_{,\theta}$	p.u.						
Input power corrected	$P_{1,\theta}$	W						
Iron losses	P_{fe}	W						
Frict. and wind. losses corr.	$P_{fw,\theta}$	W						
Additional-load losses	P_{LL}	W						
Stator losses corrected	$P_{s,\theta}$	W						
Rotor losses corrected	$P_{r,\theta}$	W						
Power factor	cos φ	%						
Efficiency	η	%						

Tested by: ____________________ Approved ____________________

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IEC 60034-2-3, *Rotating electrical machines – Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC motors*

IEC 60044 (all parts), *Instrument transformers*

IEC 60072-1, *Rotating electrical machines – Dimensions and output series – Part 1: Frame numbers 56 to 400 and flange numbers 55 to 1080*

IEC 60085, *Electrical insulation – Thermal evaluation and designation*

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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MACHINES ÉLECTRIQUES TOURNANTES –

Partie 2-1: Méthodes normalisées pour la détermination des pertes et du rendement à partir d'essais (à l'exclusion des machines pour véhicules de traction)

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Cette troisième édition annule et remplace la deuxième édition de l'IEC 60034-2-1 parue en 2014. Cette édition constitue une révision technique.

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Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

harmonisation de la disposition et des procédures avec l'IEC 60034-2-2 et l'IEC 60034-2-3.

Le texte de cette Norme internationale est issu des documents suivants:

Projet	Rapport de vote
2/2165/FDIS	2/2177/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

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MACHINES ÉLECTRIQUES TOURNANTES –

Partie 2-1: Méthodes normalisées pour la détermination des pertes et du rendement à partir d'essais (à l'exclusion des machines pour véhicules de traction)

1 Domaine d'application

La présente partie de l'IEC 60034 a pour objet de définir les méthodes de détermination du rendement à partir d'essais et également de spécifier les méthodes qui permettent de déterminer des pertes spécifiques.

Le présent document s'applique aux machines à courant continu ainsi qu'aux machines à courant alternatif, synchrones et à induction, de toutes dimensions, qui entrent dans le domaine d'application de l'IEC 60034-1 et assignées pour un fonctionnement sur secteur.

NOTE Ces méthodes peuvent s'appliquer à d'autres types de machines, telles que les commutatrices, les moteurs à collecteurs à courant alternatif et les moteurs à induction monophasés.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60027-1, *Symboles littéraux à utiliser en électrotechnique – Partie 1: Généralités*

IEC 60034-1:2022, *Machines électriques tournantes – Partie 1: Caractéristiques assignées et caractéristiques de fonctionnement*

IEC 60034-4-1:2018, *Machines électriques tournantes – Partie 4-1: Méthodes pour la détermination, à partir d'essais, des grandeurs des machines synchrones à excitation électrique*

IEC 60034-19, *Machines électriques tournantes – Partie 19: Méthodes spécifiques d'essai pour machines à courant continu à alimentation conventionnelle ou redressée*

IEC 60034-29, *Machines électriques tournantes – Partie 29: Techniques par charge équivalente et par superposition – Essais indirects pour déterminer l'échauffement*

IEC 60034-30-1, *Machines électriques tournantes – Partie 30-1: Classes de rendement pour les moteurs à courant alternatif alimentés par le réseau (code IE)*

IEC 60051 (toutes les parties), *Appareils de mesure électriques indicateurs analogiques à action directe et leurs accessoires*

IEC 60051-1, *Appareils de mesure électriques indicateurs analogiques à action directe et leurs accessoires – Partie 1: Définitions et exigences générales communes à toutes les parties*

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3 Termes et définitions

Pour les besoins du présent document, les termes et définitions de l'IEC 60034-1 et de l'IEC 60051-1 ainsi que les suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1
rendement
rapport de la puissance de sortie à la puissance d'entrée, exprimé dans les mêmes unités, et généralement exprimé en pourcentage

3.2
détermination directe du rendement
méthode dans laquelle la détermination du rendement est effectuée en mesurant directement la puissance d'entrée et la puissance de sortie

3.3
essai en opposition à double alimentation
essai dans lequel deux machines identiques sont couplées mécaniquement, les pertes totales des deux machines étant calculées par la différence entre les puissances électriques que l'une absorbe et que l'autre fournit

3.4
détermination indirecte du rendement
méthode dans laquelle la détermination du rendement est effectuée en mesurant la puissance d'entrée ou la puissance de sortie et en déterminant les pertes totales. Ces pertes sont ajoutées à la puissance de sortie, donnant ainsi la puissance d'entrée, ou soustraites de la puissance d'entrée, donnant ainsi la puissance de sortie

3.5
essai en opposition à simple alimentation
essai dans lequel deux machines identiques sont couplées mécaniquement, et connectées toutes deux au même réseau. Les pertes totales des deux machines sont considérées comme la puissance d'entrée fournie par ce réseau

3.6
essai à vide
essai dans lequel une machine fonctionne en moteur sans fournir de puissance mécanique utile sur l'arbre, ou dans lequel une machine fonctionne en génératrice avec ses bornes en circuit ouvert

3.7
essai au facteur de puissance nul
essai à vide effectué sur une machine synchrone surexcitée qui fonctionne à un facteur de puissance très voisin de zéro

3.8
méthode du circuit équivalent
essai sur une machine à induction dans lequel les pertes sont déterminées à l'aide d'un modèle de circuit équivalent

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3.9
essai avec rotor retiré et essai de rotation inverse
essai combiné sur une machine à induction dans lequel les pertes supplémentaires en charge sont déterminées à partir d'un essai avec rotor retiré et d'un essai avec le rotor qui opère dans le sens inverse du champ magnétique tournant du stator

3.10
essai de court-circuit
essai sur une machine synchrone dans lequel une machine fonctionne en génératrice avec ses bornes en court-circuit

3.11
essai à rotor bloqué
essai dans lequel le rotor est bloqué pour empêcher toute rotation

3.12
essai Eh-star
essai dans lequel le moteur fonctionne en connexion en étoile sur une tension de déséquilibre

3.13
pertes

3.13.1
pertes totales
P_{T}
différence entre la puissance d'entrée et la puissance de sortie, équivalente à la somme des pertes constantes (voir 3.13.2), des pertes en charge (voir 3.13.4), des pertes supplémentaires en charge (voir 3.13.5) et des pertes dans le circuit d'excitation (voir 3.13.3)

3.13.2
pertes constantes
P_{c}
pertes qui incorporent la somme des pertes par ventilation, des pertes par frottement et des pertes dans le fer

Note 1 à l'article: Même si ces pertes varient en fonction de la tension et de la charge, elles sont traditionnellement appelées pertes "constantes" et le terme est retenu dans le présent document.

3.13.2.1
pertes dans le fer
P_{fe}
pertes dans le fer dans les parties actives et pertes supplémentaires à vide dans les autres parties magnétiques et conductrices

3.13.2.2
pertes par frottement et par ventilation
P_{fw}
pertes qui incorporent la somme des pertes par ventilation et par frottement

3.13.2.2.1
pertes par frottement
pertes dues au frottement (paliers et balais, si non relevés dans les conditions assignées), à l'exclusion des pertes dans un système de graissage séparé

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3.13.2.2.2
pertes par ventilation
pertes totales dues au frottement aérodynamique dans toutes les parties de la machine, y compris la puissance absorbée par les ventilateurs montés sur l'arbre et dans les machines auxiliaires qui font partie intégrante de la machine

Note 1 à l'article: Il convient de mentionner séparément les pertes dans un système de ventilation séparé.

Note 2 à l'article: Pour les machines refroidies indirectement ou directement à l'hydrogène, voir l'IEC 60034-1.

3.13.3
pertes dans le circuit d'excitation

3.13.3.1
pertes dans le circuit d'excitation
$\boldsymbol{P}_{\mathbf{e}}$
somme des pertes dans l'enroulement d'excitation (voir 3.13.3.2), des pertes dans l'excitatrice (voir 3.13.3.3) et, pour les machines synchrones, des pertes électriques éventuelles dans les balais (voir 3.13.3.5)

3.13.3.2
pertes dans l'enroulement d'excitation
$\boldsymbol{P}_{\mathbf{f}}$
les pertes dans l'enroulement d'excitation (de champ) sont égales au produit du courant d'excitation I_{e} par la tension d'excitation U_{e}

3.13.3.3
pertes dans l'excitatrice
$\boldsymbol{P}_{\mathbf{Ed}}$
les pertes dans l'excitatrice pour les différents systèmes d'excitation (voir Annexe B) sont définies comme suit:

a) excitatrice entraînée par l'arbre

les pertes dans l'excitatrice sont la puissance absorbée par l'excitatrice sur son arbre (déduction faite des pertes par frottement et par ventilation), à laquelle s'ajoute la puissance $P_{1\mathrm{E}}$ fournie par une source séparée au niveau de ses bornes d'enroulement d'excitation, moins la puissance utile fournie par l'excitatrice à ses bornes. La puissance utile aux bornes de l'excitatrice est égale aux pertes dans l'enroulement d'excitation, selon 3.13.3.2, auxquelles s'ajoutent (dans le cas d'une machine synchrone) les pertes électriques dans les balais, selon 3.13.3.5

Note 1 à l'article: Si l'excitatrice peut être désaccouplée et soumise à l'essai séparément, ses pertes peuvent être déterminées conformément au 7.1.3.2.1.5.

Note 2 à l'article: Lorsque l'excitatrice utilise des alimentations auxiliaires séparées, leurs consommations sont à inclure dans les pertes dans l'excitatrice, sauf si elles sont prises en compte avec la consommation des auxiliaires de la machine principale.

b) excitatrice sans balai

les pertes dans l'excitatrice sont la puissance absorbée par l'excitatrice sur son arbre, déduction faite des pertes par frottement et par ventilation (lorsque l'essai correspondant est réalisé sur l'ensemble machine principale-excitatrice), à laquelle s'ajoute la puissance électrique $P_{1\mathrm{E}}$ fournie par une source séparée éventuelle absorbée par son enroulement de champ ou son enroulement du stator (dans le cas d'une excitatrice à induction), moins la puissance utile fournie par l'excitatrice aux bornes du convertisseur tournant de puissance

Note 3 à l'article: Lorsque l'excitatrice utilise des alimentations auxiliaires séparées, leurs consommations sont à inclure dans les pertes dans l'excitatrice, sauf si elles sont prises en compte avec la consommation des auxiliaires de la machine principale.

Note 4 à l'article: Si l'excitatrice peut être désaccouplée et soumise à l'essai séparément, ses pertes peuvent être déterminées conformément au 7.1.3.2.1.

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c) excitatrice tournante séparée

les pertes dans l'excitatrice sont la différence entre la puissance absorbée par le moteur d'entraînement, à laquelle s'ajoute la puissance absorbée par les alimentations auxiliaires séparées, des machines d'entraînement et entraînées, y compris la puissance fournie par une source séparée à leurs bornes d'enroulement d'excitation, et la puissance d'excitation fournie selon 3.13.3.2 et 3.13.3.4. Les pertes dans l'excitatrice peuvent être déterminées conformément au 7.1.3.2.1

d) système d'excitation statique

excitatrice statique

les pertes dans le système d'excitation sont la différence entre la puissance électrique fournie par sa source de puissance, à laquelle s'ajoute la puissance absorbée par les alimentations auxiliaires séparées, et l'excitation fournie selon 3.13.3.2 et 3.13.3.4

Note 5 à l'article: Dans le cas de systèmes alimentés par des transformateurs, les pertes dans le transformateur doivent être incluses dans les pertes dans l'excitatrice.

e) excitation en provenance d'un enroulement auxiliaire

excitatrice à partir d'un enroulement auxiliaire

les pertes dans l'excitatrice sont les pertes dans le cuivre dans l'enroulement auxiliaire (secondaire) et les pertes supplémentaires dans le fer produites par l'augmentation des harmoniques de flux. Les pertes supplémentaires dans le fer sont la différence entre les pertes qui se produisent lorsque l'enroulement auxiliaire est chargé et lorsqu'il est déchargé

Note 6 à l'article: Dans la mesure où la séparation de la composante des pertes d'excitation est difficile, il est recommandé de considérer ces pertes comme faisant partie intégrante des pertes dans le stator lors de la détermination de l'ensemble des pertes.

Dans les cas c) et d), les pertes éventuelles de la source d'excitation ou dans les connexions entre la source et les balais (machine synchrone) ou entre la source et les bornes de l'enroulement d'excitation (machine à courant continu) ne sont pas prises en compte.

Si l'excitation est fournie par un système avec des composants tels que ceux décrits de b) à e), les pertes dans l'excitatrice doivent inclure les pertes correspondantes des composants qui appartiennent aux catégories énumérées à l'Annexe B si applicables

3.13.3.4
puissance d'excitation fournie séparément
P_{1E}
la puissance d'excitation P_{1E} fournie par une source de puissance séparée est:

– pour les types d'excitatrices a) et b), la puissance d'excitation dans l'excitatrice (excitatrice à courant continu ou synchrone), ou la puissance d'entrée de l'enroulement du stator (excitatrice à induction). Elle couvre une partie des pertes dans l'excitatrice P_{Ed} (et d'autres pertes dans les excitatrices à induction), tandis qu'une plus grande partie de P_e est fournie par l'arbre;
– pour les types d'excitatrices c) et d), égale aux pertes dans le circuit d'excitation, $P_{1E} = P_e$;
– pour le type d'excitatrice e), $P_{1E} = 0$, la puissance d'excitation étant fournie entièrement par l'arbre. $P_{1E} = 0$ également pour les machines avec une excitation à aimants permanents.

Les types d'excitatrices doivent être conformes au 3.13.3.3

3.13.3.5
pertes dans les balais (circuit d'excitation)
P_b
pertes électriques dans les balais (y compris les pertes de contact) de machines synchrones à excitation séparée

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3.13.4
pertes en charge

3.13.4.1
pertes en charge
P_L
somme des pertes dans l'enroulement (I^2R) (voir 3.13.4.2) et des pertes électriques éventuelles dans les balais (voir 3.13.3.5)

3.13.4.2
pertes dans l'enroulement
les pertes dans l'enroulement sont les pertes I^2R:

– dans le circuit d'induit des machines à courant continu;
– dans les enroulements du stator et du rotor des machines à induction;
– dans les enroulements d'induit et de champ des machines synchrones

3.13.4.3
pertes dans les balais
P_b
pertes électriques dans les balais (y compris les pertes de contact) dans le circuit d'induit des machines à courant continu et dans les machines à induction à rotor bobiné

3.13.5
pertes supplémentaires en charge
P_{LL}
pertes produites par le courant de charge dans le fer actif et les autres parties magnétiques et conductrices autres que les conducteurs, pertes par courants de Foucault dans les conducteurs d'enroulements dues aux pulsations de flux qui dépendent des courants de charge, et pertes supplémentaires dans les balais dues à la commutation

Note 1 à l'article: Ces pertes ne comprennent pas les pertes supplémentaires à vide du 3.13.2.2.

3.13.6
pertes en court-circuit
P_{sc}
pertes qui dépendent du courant dans une machine synchrone et dans une machine à courant continu, lorsque l'enroulement d'induit est court-circuité

3.14
grandeurs d'essai <machines à courant alternatif polyphasé>

3.14.1
tension aux bornes
pour les machines à courant alternatif polyphasé, moyenne arithmétique des tensions de ligne

3.14.2
courant de ligne
pour les machines à courant alternatif polyphasé, moyenne arithmétique des courants de ligne

3.14.3
résistance entre lignes
pour les machines à courant alternatif polyphasé, moyenne arithmétique des résistances mesurées entre chaque paire de bornes

Note 1 à l'article: Pour les machines triphasées connectées en Y, la résistance de phase représente 0,5 fois la résistance entre lignes. Pour les machines connectées en Δ, la résistance de phase représente 1,5 fois la résistance entre lignes.

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Note 2 à l'article: Les Articles 6 et 7 donnent des explications et des formules pour les machines triphasées, sauf spécification contraire.

3.14.4
échauffement
température de la machine moins la température de l'agent de refroidissement (fluide de refroidissement) telle que définie par l'IEC 60034-1

4 Symboles et abréviations

4.1 Symboles

$\cos \varphi$	est le facteur de puissance[1]
f	est la fréquence d'alimentation, Hz
I	est le courant de ligne (moyenne de toutes les phases), A
k_{θ}	est le facteur de correction de température
n	est la vitesse de fonctionnement, s^{-1}
p	est le nombre de paires de pôles
P	est la puissance, W
P_0	est la puissance d'entrée à vide, W
P_1	est la puissance d'entrée, à l'exclusion de l'excitation[2], W
P_2	est la puissance de sortie, W
P_b	correspond aux pertes dans les balais, W
P_D	est la puissance de sortie (puissance sur l'arbre) d'un moteur d'entraînement, W
P_e	correspond aux pertes dans le circuit d'excitation, W
P_{1E}	est la puissance d'excitation fournie par une source séparée, W,
P_{Ed}	correspond aux pertes dans l'excitatrice, W
P_{el}	est la puissance électrique, à l'exclusion de l'excitation, W
P_f	correspond aux pertes dans l'enroulement d'excitation (de champ), W
P_{fe}	correspond aux pertes dans le fer, W
P_{fw}	correspond aux pertes par frottement et par ventilation, W
P_c	correspond aux pertes constantes, W
P_L	correspond aux pertes en charge, W
P_{Lr}	correspond aux pertes résiduelles, W
P_{LL}	correspond aux pertes supplémentaires en charge, W
P_{sc}	correspond aux pertes en court-circuit, W
P_{mech}	est la puissance mécanique, W
P_T	correspond aux pertes totales, W

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[1] Cette définition prend pour hypothèse une tension et un courant sinusoïdaux.

[2] Sauf spécification contraire, les essais du présent document sont décrits pour le fonctionnement en mode moteur, où P_1 et P_2 sont respectivement la puissance d'entrée électrique et la puissance de sortie mécanique.

P_w	correspond aux pertes dans l'enroulement, W, où l'indice w est généralement remplacé par a, f, e, s ou r (voir 4.2)
R	est une résistance d'enroulement, Ω
R_{eh}	est la valeur réelle de la résistance auxiliaire pour l'essai Eh-star (voir 6.2.5), Ω
R'_{eh}	est la valeur type de la résistance auxiliaire, Ω
R_f	est la résistance d'enroulement de champ, Ω
R_{ll}	est la résistance entre lignes (moyenne de toutes les phases), Ω
R_{ph}	est la résistance de phase (moyenne de toutes les phases), Ω
s	est le glissement, en valeur par unité de vitesse synchrone
T	est le couple de la machine, N·m
T_d	est la valeur lue du dispositif de mesure de couple, N·m
U	est le tension aux bornes (moyenne de toutes les phases), V
U_0	est la tension aux bornes à vide (moyenne de toutes les phases), V
U_N	est la tension assignée aux bornes, V
X	est la réactance, Ω
$\underline{Z} = R + j \times X$	est l'indication pour une grandeur complexe (impédance, par exemple)
$Z = \lvert\underline{Z}\rvert = \sqrt{R^2 + X^2}$	est la valeur absolue d'une grandeur complexe (impédance, par exemple)
Z	est l'impédance, Ω
α	est un coefficient de température
η	est le rendement
θ_0	est la température initiale des enroulements, °C
θ_a	est la température ambiante, °C
θ_c	est la température d'entrée du fluide de refroidissement primaire, °C
θ_w	est la température des enroulements, °C
τ	est une constante de temps, s

4.2 Indices supplémentaires

Les indices suivants peuvent être ajoutés aux symboles afin de clarifier la fonction de la machine et de différencier les valeurs.

Composants de la machine:

a induit

e excitation

f enroulement de champ

r rotor

s stator

w enroulement

U, V, W désignations de phases

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Catégories de machines:

B	survolteur
E	excitatrice
G	génératrice
M	moteur

Conditions de fonctionnement:

0	à vide
1	entrée
2	sortie
av	moyen, moyenne
d	dissipé
el	électrique
i	interne
k	court-circuit
L	charge d'essai
lr	rotor bloqué
mech	mécanique
N	assigné
red	sous tension réduite
t	essai
zpf	essai au facteur de puissance nul
θ	corrigé pour une température du fluide de refroidissement de référence.

NOTE D'autres indices supplémentaires sont introduits dans les paragraphes correspondants.

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5 Exigences fondamentales

5.1 Détermination directe et indirecte du rendement

Les essais peuvent être regroupés dans les trois catégories suivantes:

a) mesure de la puissance d'entrée et de la puissance sortie d'une seule machine. Ceci implique la mesure directe de la puissance électrique ou mécanique qui entre dans une machine, et de la puissance mécanique ou électrique qui provient d'une machine;

b) mesure de la puissance électrique d'entrée et de sortie sur deux machines identiques connectées mécaniquement en opposition. Ceci a pour objectif d'éliminer la mesure de la puissance mécanique absorbée ou fournie par la machine;

c) détermination des pertes réelles dans une machine dans des conditions déterminées. Il ne s'agit généralement pas des pertes totales, mais cela comprend certaines composantes de pertes.

Les méthodes de détermination du rendement des machines sont fondées sur un certain nombre d'hypothèses. Par conséquent, il n'est pas recommandé d'effectuer une comparaison entre les valeurs de rendement obtenues par différentes méthodes, dans la mesure où les chiffres peuvent ne pas nécessairement s'accorder.

5.2 Incertitude

L'incertitude, telle qu'utilisée dans la présente norme, est l'incertitude de la détermination d'un rendement réel. Elle reflète les variations dans la procédure d'essai et l'équipement d'essai.

Même si l'incertitude doit être exprimée en fonction d'une valeur numérique, une telle exigence nécessite des essais suffisants pour déterminer des valeurs représentatives et comparatives.

5.3 Méthodes préférentielles et méthodes pour essais d'acceptation spécifiques au client, essais sur le terrain ou essais individuels de série

Il est difficile d'établir des règles spécifiques pour la détermination du rendement. Le choix de l'essai à réaliser dépend des informations exigées, de l'exactitude exigée, du type et de la taille de la machine impliquée et de l'équipement d'essai disponible sur le terrain (alimentation, charge ou machine d'entraînement).

Dans les paragraphes suivants, les méthodes d'essai adaptées aux machines asynchrones et synchrones sont séparées des méthodes préférentielles et des méthodes pour les essais d'acceptation spécifiques au client, les essais sur le terrain ou les essais individuels de série.

5.4 Alimentation électrique

5.4.1 Tension

La tension d'alimentation doit être conforme au 7.2 (et au 8.3.1 pour les essais thermiques) de l'IEC 60034-1:2022.

5.4.2 Fréquence

Au cours des essais, la fréquence d'alimentation moyenne doit être égale à ±0,1 % de la fréquence exigée pour l'essai en cours de réalisation.

5.5 Instrumentation

5.5.1 Généralités

Les conditions d'environnement doivent se situer dans la plage recommandée indiquée par le fabricant de l'appareil. Le cas échéant, des corrections de température conformément à la spécification du fabricant de l'appareil doivent être appliquées.

Les appareils de mesure numériques doivent être utilisés dans toute la mesure du possible.

Pour les appareils de mesure analogiques, l'exactitude est généralement exprimée comme un pourcentage de la pleine échelle, la plage des appareils de mesure choisis devant être la plus restreinte possible.

La pleine échelle des appareils, notamment des capteurs de courant, doit être adaptée à la puissance de la machine en essai.

Pour les appareils de mesure analogiques, il convient que les valeurs lues se situent dans le tiers supérieur de la plage de mesure de l'instrument.

Dans le cadre des essais de machines électriques en charge, des fluctuations lentes de la puissance de sortie et des autres grandeurs mesurées peuvent être inévitables. Par conséquent, pour chaque point de charge, de nombreuse lectures (en général plusieurs centaines de lectures) doivent être effectuées automatiquement par un compteur numérique approprié sur une période de plusieurs cycles de fluctuations d'au moins 5 s, mais de 60 s au maximum, et cette moyenne doit être utilisée pour la détermination du rendement.

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5.5.2 Appareils de mesure pour les grandeurs électriques

Les appareils de mesure doivent avoir l'équivalent d'une classe d'exactitude de 0,2 dans le cas d'un essai direct et de 0,5 dans le cas d'un essai indirect, conformément à l'IEC 60051. L'appareil de mesure doit avoir une incertitude globale maximale de 0,2 % de lecture au facteur de puissance 1,0 et doit inclure toutes les erreurs des transformateurs de mesure ou des transducteurs, s'ils sont utilisés.

NOTE Pour un essai individuel de série tel que celui décrit dans l'IEC 60034-1, une classe d'exactitude de 0,5 est suffisante.

Dans le cas des machines à courant alternatif, sauf spécification contraire dans la présente norme, la moyenne arithmétique des courants et tensions de ligne doit être utilisée.

5.5.3 Mesure du couple

Le dispositif de mesure de couple doit avoir une classe minimale de 0,2. Le couple minimal mesuré doit être égal à au moins 10 % du couple nominal du couplemètre. Cela s'applique également aux mesures de charges partielles, car l'incertitude de l'appareil augmente lorsque les valeurs lues sont faibles. Si un appareil de classe supérieure est utilisé, la plage des valeurs de couple autorisée peut être élargie en conséquence.

NOTE Par exemple, une classe de 0,1 signifie 5 % du couple nominal du couplemètre.

Le dispositif de mesure de couple autorisé est un couplemètre en ligne ou un capteur de couple de réaction entre la machine et sa base. Dans ce dernier cas, la machine est directement couplée à la charge. Voir Figure 2.

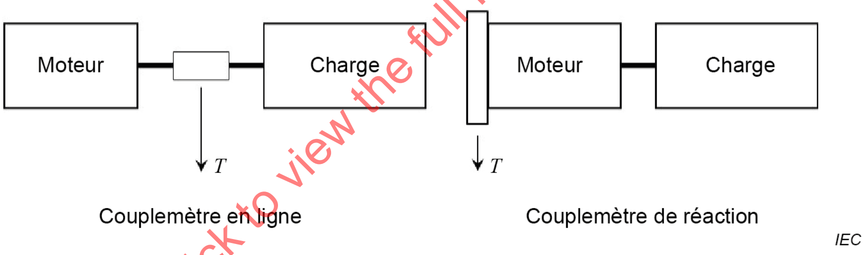

Figure 1 – Dispositifs de mesure de couple

Il doit être noté que la température du capteur de couple (c'est-à-dire due à la proximité du rotor) peut être supérieure à la température ambiante et est reconnue comme contribuant de façon significative à l'incertitude globale. Dans ce cas, la contribution de la température à l'incertitude doit être limitée à 0,15 % de la pleine échelle. Si cela n'est pas possible, une correction de température appropriée doit être appliquée.

Il convient de réduire le plus possible les charges parasites par l'alignement de l'arbre et l'utilisation de couplages flexibles.

5.5.4 Mesure de la vitesse et de la fréquence

L'instrumentation utilisée pour mesurer la fréquence d'alimentation doit avoir une exactitude de ±0,1 % de la pleine échelle. Il convient que la mesure de la vitesse soit exacte à 0,1 tour par minute.

NOTE Pour les machines asynchrones, la mesure du glissement par une méthode adaptée peut remplacer la mesure de la vitesse (voir Annexe C).

5.5.5 Mesure de la température

Les appareils utilisés pour mesurer les températures doivent avoir une exactitude de ±1 K.

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5.6 Unités

Sauf spécification contraire, les unités des valeurs sont les unités SI répertoriées dans l'IEC 60027-1.

5.7 Résistance

5.7.1 Résistance d'essai

La résistance d'enroulement R est la valeur ohmique, déterminée par des méthodes appropriées.

Pour les machines à courant continu, R est la résistance totale de tous les enroulements parcourus par le courant d'induit (induit, commutation, enroulement de compensation, enroulement composé).

Pour les machines à courant continu et les machines synchrones, R_f est la résistance d'enroulement de champ.

Pour les machines à courant alternatif polyphasé, $R = R_\mathrm{ll}$ est la résistance moyenne entre lignes de l'enroulement du stator ou de l'enroulement d'induit, conformément au 3.14.3. Dans le cas de machines à induction à rotor bobiné, $R_\mathrm{r,ll}$ est la résistance moyenne entre lignes du rotor.

La résistance mesurée à la fin de l'essai thermique doit être déterminée dès que possible, au plus tard après deux fois l'intervalle spécifié dans le Tableau 6 de l'IEC 60034-1:2022. Des lectures supplémentaires doivent être effectuées à intervalles d'environ 1 min, jusqu'à ce que les valeurs lues aient commencé à diminuer sensiblement par rapport à la valeur maximale correspondante. Une courbe de ces valeurs lues doit être tracée en fonction du temps et extrapolée à zéro. La valeur de la température ainsi obtenue doit être considérée comme la température à l'arrêt.

La température mesurée des enroulements doit être déterminée conformément au 5.7.2.

5.7.2 Température des enroulements

La température mesurée des enroulements doit être déterminée par l'une des méthodes suivantes (indiquées par ordre de préférence):

a) température déterminée à partir de la résistance d'essai en charge assignée R_N par la procédure d'extrapolation décrite en 5.7.1;

b) température mesurée directement soit par ETD ou soit par thermocouple; si la température est mesurée par plusieurs ETD ou thermocouples, la moyenne de toutes les valeurs lues doit être utilisée;

c) température déterminée conformément au point a) sur une seconde machine de même construction et de même conception électrique;

d) si la capacité en charge n'est pas disponible, déterminer la température de fonctionnement conformément à l'IEC 60034-29;

e) si la résistance d'essai en charge assignée R_N ne peut pas être mesurée directement, la température des enroulements doit être admise par hypothèse comme étant égale à la température de référence de la classe thermique assignée indiquée dans le Tableau 1.

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Tableau 1 – Température de référence

Classe thermique du système d'isolation	Température de référence °C
130 (B)	95
155 (F)	115
180 (H)	135

Si l'échauffement assigné ou la température assignée est spécifié(e) à une valeur qui correspond à une classe thermique inférieure à la classe du système utilisé dans la construction, alors la température de référence doit être celle de la classe thermique la plus basse.

Les moteurs qui sont soumis à des essais de vérification à des fins de réglementation ne doivent pas être démontés. Dans ce cas, la mesure de la température des enroulements doit être obtenue en modifiant la méthode de résistance.

5.7.3 Correction par rapport à la température du fluide de refroidissement de référence

Si cela est exigé, les valeurs de résistance d'enroulement enregistrées au cours de l'essai doivent être rapportées à une température de référence normalisée de 25 °C. Le facteur de correction pour régler la résistance d'enroulement (et le glissement en cas de machines à induction à cage) par rapport à une température du fluide de refroidissement de référence normalisée de 25 °C doit être déterminé par

$$k_\theta = \frac{235 + \theta_w + 25 - \theta_c}{235 + \theta_w} \tag{1}$$

où

k_θ est le facteur de correction de température pour les enroulements;

θ_c est la température du fluide de refroidissement primaire au cours de l'essai;

θ_w est la température des enroulements, conformément au 5.7.2.

La constante de température 235 est valable pour le cuivre; il convient de la remplacer par 225 pour les conducteurs en aluminium.

Pour les machines dont le fluide de refroidissement primaire ou secondaire est l'eau, la température de référence de l'eau doit être de 25 °C, conformément au Tableau 5 de l'IEC 60034-1:2022. D'autres valeurs peuvent être spécifiées par accord.

5.8 État de la machine en essai et catégories d'essais

Les essais doivent être effectués sur une machine assemblée avec les composants essentiels en place, afin d'obtenir des conditions d'essai identiques aux conditions normales de fonctionnement ou très proches de celles-ci.

Pour la manipulation des systèmes d'étanchéité pour les mesures liées à la classification du rendement, voir l'IEC 60034-30-1.

Il est préférable de choisir la machine de manière aléatoire à partir d'une production en série, sans considérations particulières.

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Les sous-essais qui constituent une procédure d'essai doivent être réalisés selon l'ordre indiqué. Il n'est pas essentiel de réaliser les essais immédiatement l'un après l'autre. Cependant, si les sous-essais sont réalisés avec retard, alors les conditions thermiques spécifiées doivent être rétablies avant d'obtenir les valeurs d'essai.

Pour les machines à balais réglables, les balais doivent être placés dans la position qui correspond aux caractéristiques assignées spécifiées. Pour les moteurs à induction avec un rotor bobiné équipé d'un dispositif de relevage des balais, les balais doivent être relevés au cours des essais, avec l'enroulement du rotor court-circuité. Pour les mesures à vide, les balais doivent être placés dans l'axe neutre sur les machines à courant continu.

Pour les machines à balais, lors de l'essai à la charge assignée et avant tout mesurage, un examen visuel doit être effectué pour vérifier si les balais sont bien fixés, et une peau appropriée est développée.

Les pertes dans les paliers dépendent des températures de fonctionnement des paliers, du type de lubrifiant et de la température du lubrifiant.

S'il est nécessaire d'indiquer les pertes dans un système de graissage séparé des paliers, il convient de les mentionner séparément.

Dans le cas de moteurs équipés de paliers de butée, seule la portion de perte dans le palier de butée produite par le moteur lui-même doit être incluse dans les pertes totales.

Les pertes par frottement dues à la charge sur la butée peuvent être incluses par accord.

Si la machine soumise à l'essai utilise un refroidissement à flux direct des paliers, ces pertes sont distribuées entre la machine soumise à l'essai et toute autre machine couplée à elle mécaniquement, telle qu'une turbine, proportionnellement aux masses de leurs parties tournantes. S'il n'y a pas de refroidissement à flux direct, la distribution des pertes dans les paliers doit être déterminée par accord, à partir de formules empiriques.

5.9 Mesures du circuit d'excitation

La détermination de la tension U_e et du courant I_e (voir 3.13.3.2) dépend des configurations du système d'excitation (voir 3.13.3.3). Lorsque cela est applicable, les valeurs d'essai doivent être enregistrées conformément à ce qui suit:

a) pour les machines entraînées par l'arbre, les excitatrices tournantes séparées, les excitatrices statiques et les excitatrices à enroulement auxiliaire (voir 3.13.3.3 a), c), d) et e)), la tension U_e et le courant I_e sont mesurés:
   - aux bornes de l'enroulement d'excitation des machines à courant continu;
   - aux bagues de l'enroulement de champ des machines synchrones;

b) pour les machines excitées par des excitatrices sans balai (voir 3.13.3.3 b)), les valeurs d'essai doivent être enregistrées par l'une des deux méthodes suivantes:
   - tension U_e mesurée à l'aide de bagues auxiliaires (provisoires) connectées aux extrémités de l'enroulement de champ. À partir de la tension et de la résistance R_e, déterminer le courant d'enroulement de champ $I_e = \frac{U_e}{R_e} = \frac{U_f}{R_f}$. La résistance d'enroulement de champ est à mesurer après l'arrêt de la machine en utilisant la procédure d'extrapolation décrite en 5.7.1;
   - tension U_e et courant I_e mesurés à l'aide de bagues de puissance, adaptées pour une mesure directe du courant d'enroulement de champ.

NOTE La différence entre U_e et U_f (chute de tension des balais) est quasiment négligeable en pratique.

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Les tensions et les courants doivent être mesurés à des températures stabilisées.

Les pertes dans le circuit d'excitation P_e sont déterminées conformément au 7.1.3.2.1.5 (machines synchrones) ou au 8.3.2.1.5 (machines à courant continu).

5.10 Température ambiante pendant les essais

Il convient que la température ambiante se situe dans la plage comprise entre 15 °C et 40 °C.

6 Méthodes d'essai pour la détermination du rendement des machines à induction

6.1 Méthodes d'essai préférentielles

6.1.1 Généralités

Le présent document définit trois différentes méthodes préférentielles avec une faible incertitude dans la plage d'application indiquée dans le Tableau 2. La méthode spécifique à utiliser dépend du type ou des caractéristiques assignées de la machine en essai:

Méthode 2-1-1A: Mesure directe des puissances d'entrée et de sortie à l'aide d'un dispositif de mesure de couple. À appliquer pour toutes les machines monophasées.

Méthode 2-1-1B: Sommation des pertes séparées. Détermination des pertes supplémentaires en charge par la méthode des pertes résiduelles. À appliquer pour toutes les machines triphasées dont la puissance de sortie assignée est inférieure ou égale à 2 MW. Voir également l'Annexe D.

Méthode 2-1-1C: Sommation des pertes séparées. Détermination des pertes supplémentaires en charge par la méthode de la valeur assignée. À appliquer pour toutes les machines triphasées dont la puissance de sortie assignée est supérieure à 2 MW.

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Tableau 2 – Machines à induction: méthodes d'essai préférentielles

Référence	Méthode	Description	Paragraphe	Application	Dispositifs exigés
2-1-1A	**Mesure directe:** **Puissances entrée-sortie**	Mesure du couple	6.1.2	Toutes les machines monophasées	Dispositif de mesure de couple pour la pleine charge
2-1-1B	**Sommation des pertes:** **Pertes résiduelles**	P_{LL} déterminées à partir des pertes résiduelles	6.1.3	Machines triphasées avec puissance de sortie assignée inférieure ou égale à 2 MW.	Dispositif de mesure de couple pour 1,25 × la pleine charge, ou machine en charge pour 1,25 × la pleine charge avec dispositif de mesure de couple
2-1-1C	**Sommation des pertes:** **Valeur assignée**	P_{LL} à partir d'une valeur assignée	6.1.4	Machines triphasées avec puissance de sortie assignée supérieure à 2 MW.	

6.1.2 Méthode 2-1-1A – Mesure directe des puissances d'entrée et de sortie

6.1.2.1 Généralités

Il s'agit d'une méthode d'essai dans laquelle la puissance mécanique P_{mech} d'une machine est déterminée par la mesure du couple sur l'arbre et de la vitesse. La puissance électrique P_{el} du stator est mesurée pendant le même essai.

Les puissances d'entrée et de sortie sont:

pour le fonctionnement en mode moteur: $P_1 = P_{el}$; $P_2 = P_{mech}$ (voir Figure 2); (2)

pour le fonctionnement en mode génératrice: $P_1 = P_{mech}$; $P_2 = P_{el}$. (3)

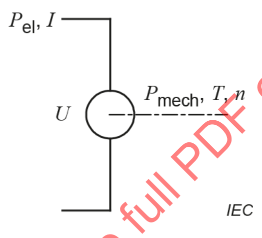

Figure 2 – Schéma pour l'essai de mesure du couple

Comme vue d'ensemble, la Figure 3 représente un organigramme pour la détermination du rendement par cette méthode d'essai.

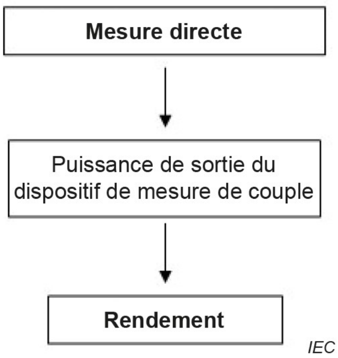

Figure 3 – Détermination du rendement selon la méthode 2-1-1A

6.1.2.2 Procédure d'essai

Coupler la machine en essai à une machine en charge avec un dispositif de mesure de couple. Faire fonctionner la machine en essai à la charge exigée jusqu'à l'obtention de l'équilibre thermique (taux de variation de 1 K ou moins par demi-heure).

Enregistrer U, I, P_{el}, n, T, θ_c.

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Immédiatement après l'essai, la dérive du dispositif de mesure du couple doit être vérifiée. En cas d'écart supérieur à la tolérance admissible du dispositif de mesure du couple, le régler et répéter les mesurages.

6.1.2.3 Détermination du rendement

Le rendement est:

$$\eta = \frac{P_2}{P_1} \qquad (4)$$

La puissance d'entrée P_1 et la puissance de sortie P_2 sont les suivantes:

pour le fonctionnement en mode moteur: $P_1 = P_{el}$; $P_2 = P_{mech}$; (5)

pour le fonctionnement en mode génératrice: $P_1 = P_{mech}$; $P_2 = P_{el}$ (6)

où

$$P_{mech} = 2\pi \times T \times n \qquad (7)$$

6.1.3 Méthode 2-1-1B – Sommation des pertes, avec détermination des pertes supplémentaires en charge selon la méthode des pertes résiduelles

6.1.3.1 Généralités

Il s'agit d'une méthode d'essai dans laquelle le rendement est déterminé par la sommation des pertes séparées. Les composantes de pertes respectives sont les suivantes:

– pertes dans le fer;
– pertes par ventilation et par frottement;
– pertes dans le cuivre du stator et du rotor;
– pertes supplémentaires en charge.

Comme vue d'ensemble, la Figure 4 représente un organigramme pour la détermination du rendement par cette méthode d'essai.

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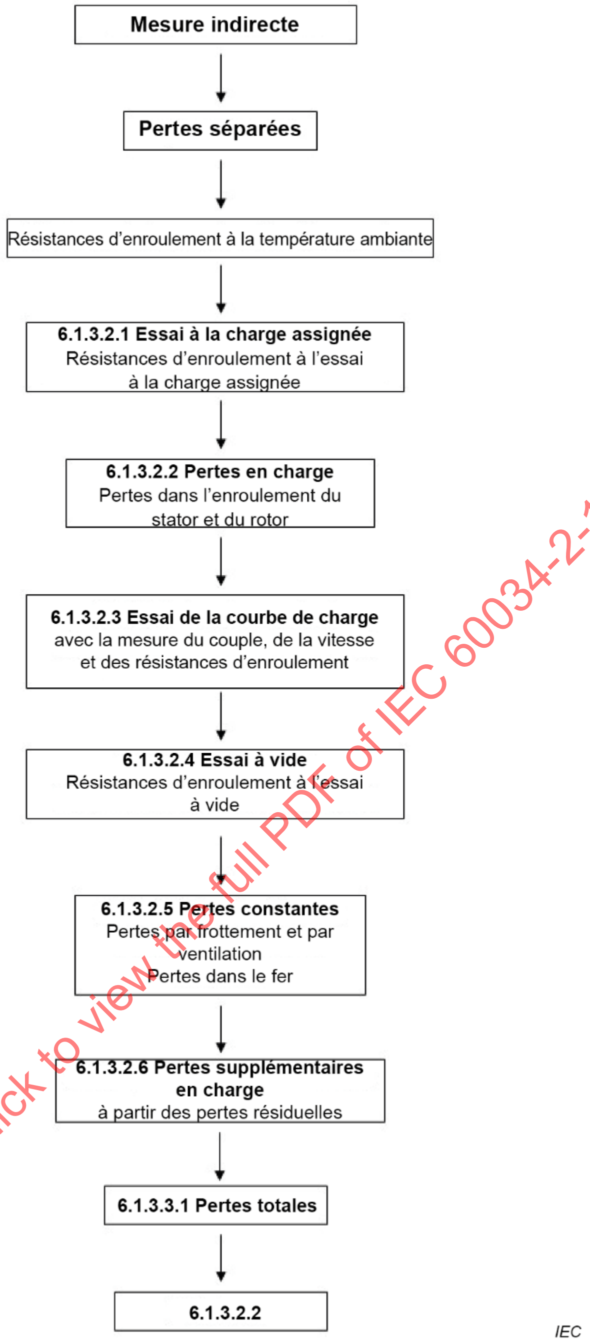

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Figure 4 – Détermination du rendement selon la méthode 2-1-1B

6.1.3.2 Procédure d'essai

6.1.3.2.1 Essai à la charge assignée

Avant de démarrer cet essai en charge, mesurer la température et la résistance d'enroulement du moteur, le moteur étant à la température ambiante.

La machine doit être mise sous charge par des moyens adaptés, avec une puissance de sortie assignée, et elle doit être mise en fonctionnement jusqu'à l'obtention de l'équilibre thermique (taux de variation de 1 K ou moins par demi-heure). Enregistrer les grandeurs suivantes:

– P_1, T, I, U, n, f, θ_c, θ;

– $R_N = R$ (la résistance en essai pour la charge assignée, conformément au 5.7.1);

– θ (la température des enroulements à la charge assignée, conformément au 5.7.2).

Immédiatement après l'essai en charge, la dérive du transducteur de couple doit être vérifiée. En cas d'écart supérieur à la tolérance admissible du transducteur, le régler et répéter les mesurages.

6.1.3.2.2 Pertes en charge

6.1.3.2.2.1 Pertes dans l'enroulement du stator et correction de température

Les pertes dans l'enroulement du stator non corrigées à la charge assignée sont:

$$P_{\mathrm{s}} = 1{,}5 \times I^2 \times R \tag{8}$$

où I et R sont déterminés en 5.7.1.

Déterminer les pertes dans l'enroulement du stator en utilisant la résistance d'enroulement du stator R_{N} à partir de l'essai à la charge assignée, corrigée pour une température du fluide de refroidissement de référence de 25 °C:

$$P_{\mathrm{s},\theta} = P_{\mathrm{s}} \times k_\theta \tag{9}$$

où k_θ est la correction selon 5.7.3 pour l'enroulement du stator.

6.1.3.2.2.2 Pertes dans l'enroulement du rotor et correction de température

Pour les pertes dans l'enroulement du rotor non corrigées, utiliser la formule:

$$P_{\mathrm{r}} = \left(P_1 - P_{\mathrm{s}} - P_{\mathrm{fe}}\right) \times s \tag{10}$$

où

$$s = 1 - \frac{p \times n}{f} \tag{11}$$

P_1, n et f sont conformes à l'essai à la charge assignée;

P_{s} est conforme à l'essai en charge décrit ci-dessus;

P_{fe} est conforme au 6.1.3.2.5.

Les pertes dans l'enroulement du rotor corrigées sont déterminées en utilisant la valeur corrigée des pertes dans l'enroulement du stator:

$$P_{\mathrm{r},\theta} = \left(P_1 - P_{\mathrm{s},\theta} - P_{\mathrm{fe}}\right) \times s_\theta$$

où

P_{fe} est conforme au 6.1.3.2.5 pour une température du fluide de refroidissement de référence de 25 °C;

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$s_{\theta} = s \times k_{\theta}$ est le glissement corrigé pour une température du fluide de refroidissement de référence de 25 °C (voir 5.7.3);

k_{θ} est la correction selon 5.7.3.

6.1.3.2.2.3 Correction de température de la puissance d'entrée (pour un moteur)

Les pertes dans l'enroulement du stator et du rotor étant corrigées, la puissance d'entrée corrigée est:

$$P_{1,\theta} = P_1 - (P_s - P_{s,\theta} + P_r - P_{r,\theta}) \quad (12)$$

6.1.3.2.3 Essai de la courbe de charge

Cet essai doit être effectué immédiatement après l'essai à la charge assignée avec le moteur à la température de fonctionnement.

Si cela n'est pas possible, avant de commencer à enregistrer les données pour cet essai, l'échauffement des enroulements doit être de l'ordre de 5 K de l'échauffement initial θ_N, obtenu à partir d'un essai de température à la charge assignée.

Appliquer la charge (puissance sur l'arbre) à la machine aux six points de charge suivants: environ 125 %, 115 %, 100 %, 75 %, 50 % et 25 % de la charge assignée. Ces essais doivent être réalisés aussi rapidement que possible afin de réduire le plus possible les variations de température dans la machine pendant les essais.

NOTE 1 À titre indicatif, la charge appliquée peut varier de ±5 % par rapport aux valeurs données ci-dessus. L'impact sur l'évaluation ultérieure des pertes résiduelles est limité.

La variation de la fréquence d'alimentation entre tous les points doit être inférieure à 0,1 %.

Mesurer R avant la valeur de charge lue la plus élevée et après la valeur de charge lue la plus faible. La résistance pour une charge de 100 % et des charges supérieures doit être la valeur déterminée avant la valeur de charge lue la plus élevée. La résistance utilisée pour les charges inférieures à 100 % doit alors être déterminée comme variant de façon linéaire avec la charge, en utilisant la valeur lue avant l'essai pour la charge la plus élevée et après la valeur lue la plus faible pour une charge de 25 %.

NOTE 2 Les résistances peuvent également être déterminées en mesurant la température de l'enroulement du stator à l'aide d'un dispositif sensible à la température installé sur l'enroulement. Les résistances pour chaque point de charge peuvent alors être déterminées à partir de la résistance mesurée avant l'essai de la courbe de charge multipliée par le rapport de la température de l'enroulement à ce point de charge à la température de l'enroulement mesurée avant le début de l'essai.

Enregistrer pour chaque point de charge: U, I, P_1, n, f, T.

Les pertes dans l'enroulement du stator à chacun des points de charge sont:

$$P_s = 1{,}5 \times I^2 \times R \quad (13)$$

où I et R sont déterminés conformément au 6.1.3.2.2 pour chaque point de charge.

Pour les pertes dans l'enroulement du rotor, pour chacun des points de charge, utiliser la formule:

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$$P_r = (P_1 - P_s - P_{fe}) \times s \tag{14}$$

où

$$s = 1 - \frac{p \times n}{f} \tag{15}$$

P_1, n et f	sont conformes à l'essai de la courbe en charge;
P_s	est conforme à l'essai de la courbe de charge décrit ci-dessus;
P_{fe}	est conforme au 6.1.3.2.5.

6.1.3.2.4 Essai à vide

L'essai à vide doit être effectué sur une machine chaude immédiatement après l'essai de la courbe de charge.

En variante, l'essai peut également être réalisé avec des pertes à vide stabilisées. Les pertes à vide sont considérées comme stabilisées lorsque la puissance d'entrée à vide varie de 3 % ou moins, lorsqu'elle est mesurée à deux intervalles de 30 min successifs.

Réaliser l'essai aux huit valeurs de tension suivantes, y compris à la tension assignée, de telle sorte que:

– les valeurs d'environ 110 %, 100 %, 95 % et 90 % de la tension assignée sont utilisées pour la détermination des pertes dans le fer;
– les valeurs d'environ 60 %, 50 %, 40 % et 30 % de la tension assignée sont utilisées pour la détermination des pertes par ventilation et par frottement.

L'essai doit être effectué aussi rapidement que possible avec les lectures prises dans l'ordre décroissant de tension.

Enregistrer à chacune des valeurs de tension: U_0, I_0, P_0.

Déterminer la résistance R_0 immédiatement avant et après l'essai à vide.

La résistance d'enroulement interpolée de chaque point de tension doit être calculée en interpolant les résistances avant et après l'essai, de façon linéaire avec la puissance électrique P_0.

Pour les machines à induction, R_0 est $R_{ll,0}$. Lorsque le mesurage des résistances n'est pas réalisable en raison de résistances très faibles, les valeurs calculées sont admissibles.

NOTE Les résistances peuvent également être déterminées en mesurant la température de l'enroulement du stator à l'aide d'un dispositif sensible à la température installé sur l'enroulement. Les résistances pour chaque point de tension peuvent alors être déterminées à partir de la résistance mesurée avant l'essai à vide multipliée par le rapport de la température de l'enroulement au point de charge concerné à la température de l'enroulement mesurée avant le début de l'essai.

Pour une machine couplée, P_0 est déterminée à partir de T et n.

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6.1.3.2.5 Pertes constantes

6.1.3.2.5.1 Généralités

La soustraction des pertes dans l'enroulement à vide de la puissance d'entrée à vide donne les pertes constantes qui sont la somme des pertes par frottement, des pertes par ventilation et des pertes dans le fer. Pour chaque valeur de tension enregistrée, déterminer les pertes constantes.

$$P_{\mathrm{c}} = P_0 - P_{\mathrm{s}} = P_{\mathrm{fw}} + P_{\mathrm{fe}} \qquad (16)$$

où

$$P_{\mathrm{s}} = 1{,}5 \times I_0^2 \times R_{\mathrm{ll,0}} \qquad (17)$$

avec $R_{\mathrm{ll,0}}$ comme résistance d'enroulement interpolée à chaque point de tension.

6.1.3.2.5.2 Pertes par frottement et par ventilation

À partir des quatre points ou plus de pertes à vide consécutifs compris entre environ 60 % de la tension et 30 % de la tension, tracer une courbe des pertes constantes (P_{c}) en fonction de la tension au carré (${U_0}^2$).

Extrapoler une ligne droite jusqu'à la tension zéro. Déterminer l'intersection à la tension zéro, qui est considérée comme correspondant aux pertes par frottement et par ventilation P_{fw0} à une vitesse approximativement synchrone.

6.1.3.2.5.3 Pertes dans le fer

À partir des valeurs de tension comprises entre environ 90 % et 110 % de la tension assignée, tracer une courbe de $P_{\mathrm{fe}} = P_{\mathrm{c}} - P_{\mathrm{fw}}$ en fonction de la tension U_0.

Pour déterminer les pertes dans le fer à pleine charge, la tension interne U_{i} qui prend en compte la chute de tension résistive dans l'enroulement primaire doit être calculée:

$$U_{\mathrm{i}} = \sqrt{\left(U - \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \sin\varphi\right)^2} \quad \text{pour un moteur} \qquad (18)$$

$$U_{\mathrm{i}} = \sqrt{\left(U + \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot \sin\varphi\right)^2} \quad \text{pour une génératrice} \qquad (19)$$

où

$$\cos\varphi = \frac{P_1}{\sqrt{3} \times U \times I}; \qquad \sin\varphi = \sqrt{1 - \cos^2\varphi} \qquad (20)$$

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U, P_1, I et R proviennent de l'essai en charge selon 6.1.3.2.1.

Les pertes dans le fer à pleine charge doivent être interpolées à partir des pertes dans le fer sur la courbe de tension U_0 à la tension U_i.

NOTE Les pertes dans le fer à pleine charge peuvent être calculées à l'aide du rapport $(U_i/U_N)^2$ appliqué aux pertes dans le fer à vide.

En raison de la méconnaissance de l'inductance de fuite du stator, la tension ne prend en compte que la chute de tension résistive. Du fait du faible facteur de puissance à vide, la chute de tension résistive est négligeable pendant le mesurage proprement dit et ne doit être prise en considération que pour les valeurs de la charge.

6.1.3.2.6 Pertes supplémentaires en charge P_{LL}

6.1.3.2.6.1 Pertes résiduelles P_{Lr}

Les pertes résiduelles doivent être déterminées pour chaque point de charge en soustrayant de la puissance d'entrée: la puissance de sortie mécanique, les pertes dans l'enroulement du stator non corrigées à la résistance de l'essai, les pertes dans le fer ajustées, les pertes par ventilation et par frottement corrigées, et les pertes dans l'enroulement du rotor non corrigées qui correspondent à la valeur déterminée du glissement.

Les pertes dans le fer à chaque point de charge doivent être interpolées à partir des pertes dans le fer sur la courbe de tension U_0 à la tension U_i pour le point de charge respectif.

$$P_{Lr} = P_1 - P_2 - P_s - P_r - P_{fe} - P_{fw}\,; \tag{21}$$

$$P_2 = 2\pi \cdot T \cdot n \text{ pour un moteur et } P_1 = 2\pi \cdot T \cdot n \text{ pour une génératrice} \tag{22}$$

où

$$P_{fw} = P_{fw0} \cdot (1-s)^{2,5} \text{ avec } s = 1 - \frac{p \times n}{f} \tag{23}$$

sont les pertes par frottement et par ventilation corrigées.

6.1.3.2.6.2 Lissage des valeurs des pertes résiduelles

Les valeurs des pertes résiduelles doivent être lissées en utilisant une analyse de régression linéaire (voir Figure 5) fondée sur l'expression des pertes en fonction du carré du couple en charge conformément à la relation:

$$P_{Lr} = A \times T^2 + B \tag{24}$$

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A et B sont des constantes déterminées à partir des six points de charge à l'aide des formules suivantes:

A est la pente selon

$$A = \frac{i \cdot \sum\left(P_{Lr} \cdot T^2\right) - \sum P_{Lr} \cdot \sum T^2}{i \cdot \sum\left(T^2\right)^2 - \left(\sum T^2\right)^2} \quad (25)$$

B est l'intersection selon

$$B = \frac{\sum P_{Lr}}{i} - A \cdot \frac{\sum T^2}{i} \quad (26)$$

i est le nombre de points de charge additionnés.

Il convient que l'intersection B soit considérablement plus faible (< 50 %) que les pertes supplémentaires en charge P_{LL} au couple assigné. Sinon, la mesure peut être erronée et il convient de la vérifier.

NOTE L'intersection B peut être positive ou négative. La Figure 5 donne un exemple d'intersection B positive.

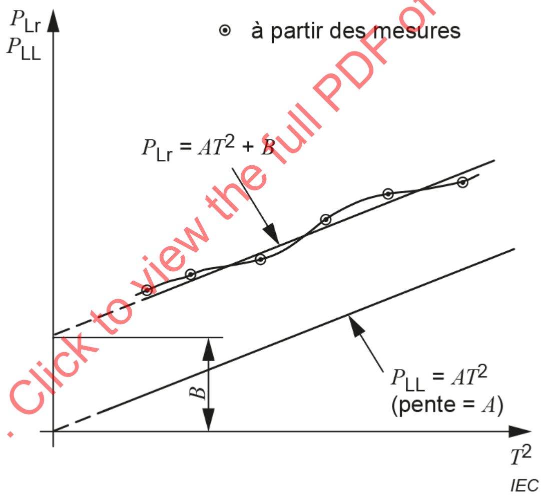

Figure 5 – Lissage des valeurs des pertes résiduelles

Le coefficient de corrélation est calculé par la formule

$$\gamma = \frac{i \cdot \Sigma\left(P_{Lr} \cdot T^2\right) - \left(\Sigma P_{Lr}\right) \cdot \left(\Sigma T^2\right)}{\sqrt{\left(i \cdot \Sigma\left(T^2\right)^2 - \left(\Sigma T^2\right)^2\right) \cdot \left(i \cdot \Sigma P_{Lr}^2 - \left(\Sigma P_{Lr}\right)^2\right)}} \quad (27)$$

Si le coefficient de corrélation γ est inférieur à 0,95, supprimer le point le plus défavorable et répéter la régression. Si γ augmente jusqu'à ≥ 0,95, utiliser la deuxième régression; si γ reste inférieur à 0,95, l'essai n'est pas satisfaisant, et les erreurs d'instrumentation ou de lectures d'essai, ou les deux, sont indiquées. Il convient d'analyser et de corriger la source de l'erreur, et il convient de répéter l'essai. Lorsque les valeurs d'essai sont suffisantes, il est possible d'avoir un coefficient de corrélation de 0,98 ou plus.

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Si la constante de pente A est établie, une valeur des pertes supplémentaires en charge pour chaque point de charge doit être déterminée à l'aide de la formule:

$$P_{LL} = A \times T^2 \tag{28}$$

6.1.3.3 Détermination du rendement

6.1.3.3.1 Pertes totales

Les pertes totales doivent être considérées comme la somme des pertes dans le fer ajustées, des pertes par frottement et par ventilation corrigées, des pertes en charge et des pertes supplémentaires en charge:

$$P_T = P_{fe} + P_{fw} + P_{s\,\theta} + P_{r\,\theta} + P_{LL}, \tag{29}$$

où

$$P_{fw} = P_{fw0} \cdot (1 - s_\theta)^{2,5} \tag{30}$$

sont les pertes par frottement et par ventilation corrigées.

6.1.3.3.2 Rendement

Le rendement est déterminé à partir de

$$\eta = \frac{P_{1,\theta} - P_T}{P_{1,\theta}} = \frac{P_2}{P_2 + P_T} \tag{31}$$

NOTE Généralement, la première expression est davantage utilisée pour un moteur, la deuxième pour une génératrice.

où

$P_{1,\theta}$ est la puissance d'entrée de température corrigée à partir de l'essai à la charge assignée;

P_2 est la puissance de sortie à partir de l'essai à la charge assignée.

6.1.4 Méthode 2-1-1C – Sommation des pertes, avec détermination des pertes supplémentaires en charge à partir d'une tolérance assignée

6.1.4.1 Généralités

À l'instar de la méthode 2-1-1B, cette méthode d'essai détermine le rendement par la sommation des pertes séparées. Comme les essais à pleine charge exigés par la méthode 2-1-1B ne sont en général pas réalisables pour les caractéristiques assignées supérieures à 2 MW, cette méthode est fondée sur un essai en charge à tension réduite et à une valeur assignée pour les pertes supplémentaires en charge. Par conséquent, l'essai à pleine charge et l'essai de courbe de charge ne sont pas exigés pour la méthode 2-1-1C.

En dehors de cela, la méthode 2-1-1C est semblable à la méthode 2-1-1B.

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Comme vue d'ensemble, la Figure 6 représente un organigramme pour la détermination du rendement par cette méthode d'essai.

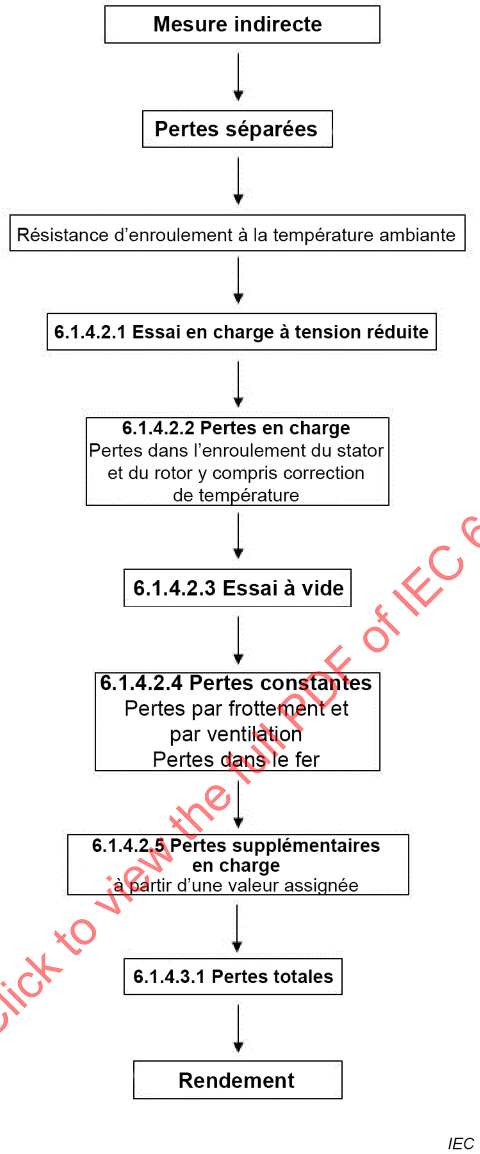

Figure 6 – Détermination du rendement selon la méthode 2-1-1C

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6.1.4.2 Procédure d'essai

6.1.4.2.1 Essai en charge à tension réduite

L'essai en charge à tension réduite constitue une méthode appropriée pour les machines de grande taille qui ne peuvent pas être soumises à l'essai à pleine charge. Les essais suivants sont exigés: un essai en charge, avec la machine fonctionnant en moteur à la tension réduite U_{red} à la vitesse assignée, un essai à vide à la même tension réduite U_{red}, et un essai à vide à la tension et à la fréquence assignées.

À l'aide de cette méthode, il est admis par hypothèse qu'à la tension réduite, tout en maintenant la vitesse constante, les courants diminuent comme la tension et la puissance diminue comme le carré de la tension.

Faire fonctionner la machine en utilisant la charge maximale disponible avec une réduction de la tension pour obtenir la vitesse assignée. La faire fonctionner pour atteindre l'équilibre thermique.

Enregistrer à la tension réduite: U_{red}, I_{red}, P_{1red}, I_{0red}, $\cos(\varphi_{0red})$.

Enregistrer à la tension assignée et à vide: U_N, I_0, $\cos(\varphi_0)$.

À partir du résultat d'un tel essai, calculer le courant en charge et la puissance absorbée à la tension assignée:

$$\underline{I} = \underline{I}_{red} \frac{U_N}{U_{red}} + \Delta\underline{I}_0 \tag{32}$$

où

$$\Delta\underline{I}_0 = -j\left(\left|\underline{I}_0\right| \sin\varphi_0 - \left|\underline{I}_{0,red}\right| \frac{U_N}{U_{red}} \sin\varphi_{0,red}\right) \tag{33}$$

$$P_1 = P_{1,red} \times \left(\frac{U_N}{U_{red}}\right)^2 \tag{34}$$

NOTE Les symboles du courant soulignés indiquent des vecteurs (voir Figure 7).

À l'aide des valeurs I et P_1 ainsi déterminées, et avec le glissement mesuré à la tension réduite, il est possible de calculer les pertes en charge, de la même façon que dans un essai en charge à la tension assignée.

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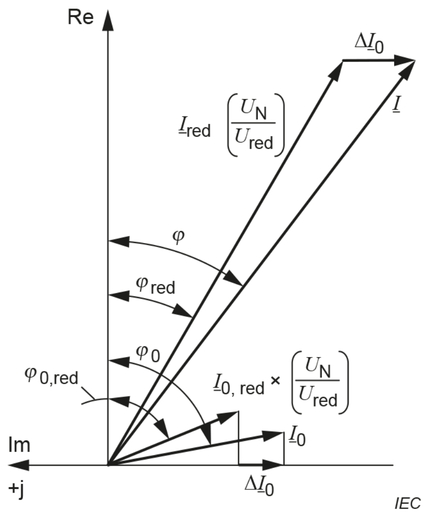

Figure 7 – Schéma vectoriel pour obtenir le vecteur courant à partir de l'essai à la tension réduite

6.1.4.2.2 Pertes en charge

La détermination des pertes en charge est similaire à celle du 6.1.3.2.2.

6.1.4.2.3 Essai à vide

L'essai à vide doit être effectué sur une machine chaude immédiatement après l'essai en charge.

L'essai à vide est similaire à celui du 6.1.3.2.4.

6.1.4.2.4 Pertes constantes

La détermination des pertes constantes est similaire à celle du 6.1.3.2.5.

6.1.4.2.5 Pertes supplémentaires en charge P_{LL}

La valeur des pertes supplémentaires en charge P_{LL} à la charge assignée doit être déterminée comme un pourcentage de la puissance d'entrée P_1 à l'aide de la courbe de la Figure 8.

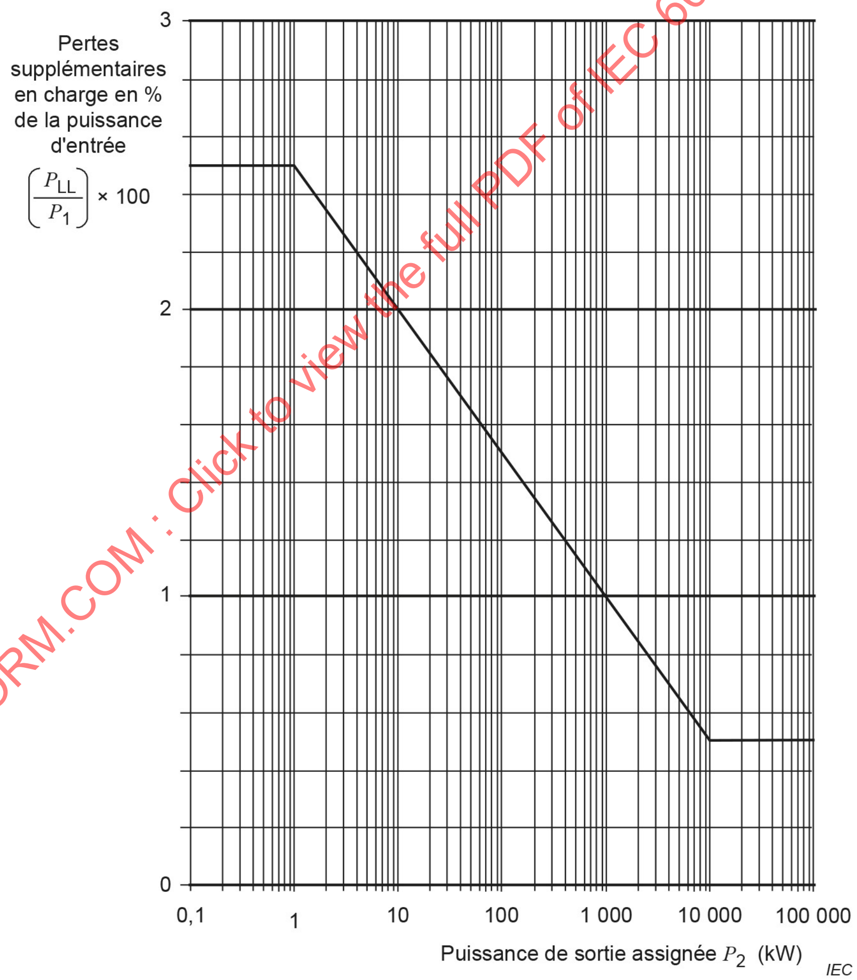

Figure 8 – Tolérance assignée pour les pertes supplémentaires en charge P_{LL}

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Les valeurs de la courbe peuvent être décrites à l'aide des formules suivantes:

pour $P_2 \leq 1$ kW $P_{LL} = P_1 \times 0{,}025$

pour 1 kW < P_2 < 10 000 kW $P_{LL} = P_1 \times \left[0{,}025 - 0{,}005 \log_{10}\left(\frac{P_2}{1\,\text{kW}}\right)\right]$

pour $P_2 \geq 10\,000$ kW $P_{LL} = P_1 \times 0{,}005$

Pour des charges autres qu'assignées, il doit être admis par hypothèse que les pertes supplémentaires en charge varient comme le carré du courant primaire moins le carré du courant à vide:

$$P_{LL}(I) = P_{LL}(I_N) \times \frac{I^2 - I_0^2}{I_N^2 - I_{0N}^2}$$

NOTE La courbe ne représente pas une moyenne, mais une enveloppe supérieure d'un grand nombre de valeurs mesurées, et elle peut, dans la plupart des cas, produire des pertes supplémentaires en charge plus élevées que 6.1.3.

6.1.4.3 Détermination du rendement

6.1.4.3.1 Pertes totales

Les pertes totales doivent être considérées comme la somme des pertes constantes, des pertes en charge et des pertes supplémentaires en charge.

$$P_T = P_c + P_s + P_r + P_{LL} \quad (35)$$

6.1.4.3.2 Rendement

Le rendement est déterminé à partir de

$$\eta = \frac{P_1 - P_T}{P_1} = \frac{P_2}{P_2 + P_T} \quad (36)$$

NOTE Généralement, la première expression est davantage utilisée pour un moteur, la deuxième pour une génératrice.

6.2 Méthodes d'essai pour les essais sur le terrain ou les essais individuels de série

6.2.1 Généralités

Ces méthodes d'essai peuvent être utilisées pour n'importe quel essai, c'est-à-dire les essais sur le terrain, les essais d'acceptation spécifiques au client ou les essais individuels de série.

De plus, les méthodes préférentielles du Tableau 2 peuvent également être utilisées hors de la plage de puissances identifiée dans le Tableau 2.

Le Tableau 3 indique les méthodes définies par le présent document.

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Tableau 3 – Machines à induction: autres méthodes

Référence	Méthode	Description	Paragraphe	Dispositifs exigés
2-1-1D	Opposition à double alimentation	Essai en opposition à double alimentation	6.2.2	Ensemble de deux machines identiques pour la pleine charge
2-1-1E	Opposition à simple alimentation	Essai en opposition à simple alimentation	6.2.3	Deux machines identiques (rotor bobiné)
2-1-1F	Rotation inverse	P_{LL} à partir de l'essai avec rotor retiré et de l'essai de rotation inverse	6.2.4	Moteur auxiliaire avec puissance assignée jusqu'à 5 × pertes totales
2-1-1G	Eh-star	P_{LL} à partir de l'essai Eh-star	6.2.5	L'enroulement doit être raccordé en connexion en étoile
2-1-1H	Circuit équivalent	Courants, puissances et glissement à partir de la méthode du circuit équivalent, P_{LL} à partir d'une valeur assignée	6.2.6	Si l'équipement d'essai pour les autres essais n'est pas disponible (aucune possibilité d'appliquer une charge assignée, pas de seconde machine)

6.2.2 Méthode 2-1-1D – Essai en opposition à double alimentation

6.2.2.1 Généralités

Comme vue d'ensemble, la Figure 9 représente un organigramme pour la détermination du rendement par cette méthode d'essai.

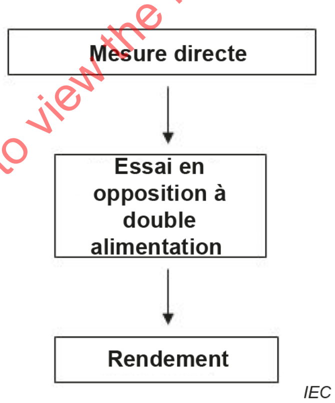

Figure 9 – Détermination du rendement selon la méthode 2-1-1D

6.2.2.2 Procédure d'essai

Coupler mécaniquement deux machines identiques ensemble (voir Figure 10).

Les essais sont réalisés avec échange des alimentations, mais avec les appareils et les transformateurs de mesure restant sur la même machine.

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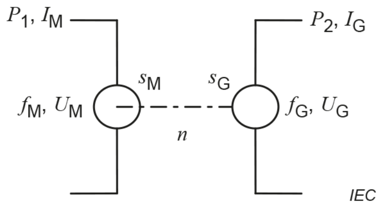

Figure 10 – Schéma pour l'essai en opposition à double alimentation

Connecter les bornes de la machine entraînée (génératrice à induction) à un ensemble de machines ou à un convertisseur, qui fournit la puissance réactive et absorbe la puissance active. Alimenter une machine (le moteur pour les caractéristiques assignées du moteur, la génératrice pour les caractéristiques assignées de la génératrice) avec une tension et une fréquence assignées; la deuxième machine doit être alimentée avec une fréquence inférieure à celle de la première machine pour le fonctionnement en mode génératrice ou supérieure pour le fonctionnement en mode moteur. La tension de la deuxième machine doit être celle nécessaire pour que le rapport de la tension assignée sur la fréquence assignée soit correct.

Inverser les connexions du moteur et de la génératrice et répéter l'essai.

Enregistrer pour chaque essai:

– U_M, I_M, P_1, f_M, s_M pour le moteur;

– U_G, I_G, P_2, f_G, s_G pour la génératrice;

– θ_c.

6.2.2.3 Détermination du rendement

Si des machines identiques sont mises en fonctionnement dans des conditions assignées essentiellement identiques, le rendement doit être calculé à partir de la moitié des pertes totales et de la moyenne de la puissance d'entrée du moteur et de la puissance de sortie de la génératrice, comme suit:

$$\eta = 1 - \frac{P_T}{\frac{P_1 + P_2}{2}} \tag{37}$$

où

$$P_T = \frac{1}{2}(P_1 - P_2) \tag{38}$$

6.2.3 Méthode 2-1-1E – Essai en opposition à simple alimentation

6.2.3.1 Généralités

Comme vue d'ensemble, la Figure 11 représente un organigramme pour la détermination du rendement par cette méthode d'essai.

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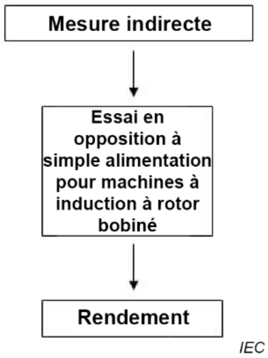

Figure 11 – Détermination du rendement selon la méthode 2-1-1E

6.2.3.2 Procédure d'essai

Cet essai s'applique aux machines à induction à rotor bobiné. Coupler mécaniquement deux machines identiques ensemble, et les connecter toutes les deux électriquement à la même alimentation électrique, de façon qu'elles fonctionnent à la vitesse assignée et à la tension assignée, l'une comme moteur et l'autre comme génératrice.

L'enroulement du rotor du moteur doit être court-circuité et l'enroulement du rotor de la génératrice doit être connecté à une alimentation polyphasée appropriée pour fournir le courant du rotor assigné à la fréquence de glissement. La puissance souhaitée du moteur est obtenue en réglant la fréquence et le courant de l'alimentation électrique à la fréquence la plus basse.

Enregistrer pour chaque essai:

– U_1, P_1, I_1 de l'alimentation à fréquence industrielle;
– U_r, I_r, P_r de l'alimentation à basse fréquence;
– P_M absorbée aux bornes du moteur;
– P_G fournie aux bornes de la génératrice;
– θ_c.

6.2.3.3 Détermination du rendement

Si des machines identiques sont mises en fonctionnement dans des conditions essentiellement assignées, le rendement est calculé en attribuant la moitié des pertes totales à chaque machine.

Calculer le rendement à partir de

$$\eta = 1 - \frac{P_T}{P_M} \quad (39)$$

où

P_M est la puissance absorbée aux bornes de la machine qui fonctionne en moteur;

P_T correspond aux pertes totales, définies comme la moitié du total absorbé, pour les machines à induction à rotor bobiné, comme suit: $P_T = \frac{1}{2}(P_1 + P_r)$.

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6.2.4 Méthode 2-1-1F – Sommation des pertes, avec détermination des pertes supplémentaires en charge par l'essai avec rotor retiré et l'essai de rotation inverse

6.2.4.1 Généralités

À l'instar de la méthode 2-1-1B, cette méthode d'essai détermine le rendement par la sommation des pertes séparées. Toutefois, dans ce cas, les pertes supplémentaires en charge sont déterminées par une combinaison de deux essais individuels: l'essai avec rotor retiré et l'essai de rotation inverse. En dehors de cela, la méthode 2-1-1F est semblable à la méthode 2-1-1B.

Comme vue d'ensemble, la Figure 12 représente un organigramme pour la détermination du rendement par cette méthode d'essai.

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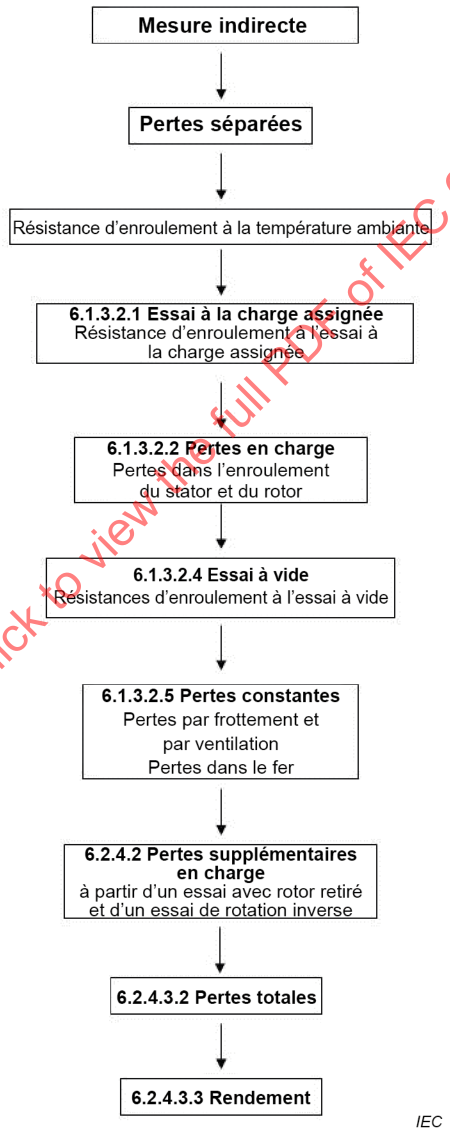

Figure 12 – Détermination du rendement selon la méthode 2-1-1F

6.2.4.2 Procédure d'essai

En dehors de la détermination des pertes supplémentaires en charge, les mêmes procédures qu'en 6.1.3.2 doivent être appliquées, sauf qu'il n'est pas nécessaire de mesurer le couple.

Les essais dont la combinaison est exigée pour la détermination des pertes supplémentaires en charge sont les suivants:

a) essai avec le rotor retiré (pour les pertes supplémentaires à la fréquence fondamentale);

b) essai avec la machine qui tourne à la vitesse synchrone à l'opposé du champ magnétique, entraînée par des moyens externes (pour les pertes aux fréquences plus élevées).

Au cours des deux essais, le stator doit être alimenté par un courant polyphasé symétrique de fréquence assignée pour quatre courants entre 25 % et 100 % du courant assigné et deux courants au-dessus qui ne représentent pas plus de 150 % du courant assigné. Calculer le courant de charge (du rotor) I_L:

$$I_L = \sqrt{I^2 - I_0^2} \tag{40}$$

où

I est la valeur du courant du stator pendant l'essai qui donne un courant de charge souhaité;

I_0 est le courant à vide à la tension assignée.

NOTE En raison de l'absence de refroidissement, le courant est généralement limité à 125 % ou 115 % pour les machines à deux pôles afin de réduire le risque de surchauffe.

6.2.4.2.1 Essai avec le rotor retiré

Pour cet essai, toutes les parties dans lesquelles des courants de Foucault peuvent être induits, par exemple les flasques et les parties des paliers, doivent être en place. Appliquer le courant de charge.

Enregistrer pour chaque courant de charge (symboles avec l'indice "rm"): $P_{1,rm}$, $I_{L,rm}$, R_{rm}, $\theta_{w,rm}$.

6.2.4.2.2 Essai de rotation inverse

Pour cet essai, coupler la machine complètement assemblée à un moteur d'entraînement dont la capacité de sortie est au moins égale aux pertes totales assignées et inférieure à cinq fois les pertes assignées de la machine à soumettre à l'essai. Pour les machines à rotor bobiné, les bornes du rotor doivent être court-circuitées.

Faire fonctionner la machine en essai à la vitesse synchrone dans le sens inverse de la rotation lorsqu'elle est alimentée en séquence de phase normale:

a) sans tension appliquée au stator jusqu'à stabilisation des pertes par frottement. Enregistrer: $P_{0,rr}$ fournie par la machine d'entraînement à I = 0;

b) avec tension appliquée au stator pour obtenir les valeurs du courant du stator égales à celles pour l'essai avec rotor retiré. Enregistrer pour tous les courants d'essai (symboles avec l'indice "rr"): $I_{L,rr}$, R_{rr}, $P_{1,rr}$;$\theta_{w,rr}$ pour le moteur en essai; $P_{D,rr}$ du moteur d'entraînement.

Le facteur de puissance faible des essais peut nécessiter une correction d'erreur de phase pour toutes les valeurs lues du wattmètre.

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6.2.4.3 Détermination du rendement

6.2.4.3.1 Pertes supplémentaires en charge

Lisser les valeurs d'essai des puissances du stator $P_{1,\text{rm}}$ and $P_{1,\text{rr}}$ et de la puissance sur l'arbre $\left(P_{\text{D,rr}} - P_{0,\text{rr}}\right)$ en appliquant une analyse de régression au logarithme des puissances et des courants, ce qui donne les relations ci-dessous:

$$P_{1,\text{rm}} = A_{\text{rm}} \times I^{N1} + B_{\text{L,rm}};\ P_{1,\text{rr}} = A_{\text{rr}} \times I^{N2} + B_{\text{L,rr}};\ \left(P_{\text{D,rr}} - P_{0,\text{rr}}\right) = A_{\text{D,rr}} \times I^{N3} + B_{\text{D,rr}} \quad (41)$$

Les puissances lissées sont alors les suivantes:

$$P_{1,\text{rm}} = A_{\text{rm}} \times I^{N1};\ P_{1,\text{rr}} = A_{\text{rr}} \times I^{N2};\ \left(P_{\text{D,rr}} - P_{0,\text{rr}}\right) = A_{\text{D,rr}} \times I^{N3} \quad (42)$$

Si les données sont exactes, chaque courbe présente une relation proche de la loi en puissance carrée entre la puissance et le courant.

Les pertes supplémentaires en charge sont: $P_{\text{LL}} = P_{\text{LL,rm}} + P_{\text{LL,rr}}$ où, pour chaque courant d'essai:

$$P_{\text{LL,rm}} = P_{1,\text{rm}} - \left(3 \times I^2 \times R_{\text{s,rm}}\right) \text{ correspond aux pertes à la fréquence fondamentale} \quad (43)$$

où

$R_{\text{s,rm}}$ est la résistance de phase du stator rapportée à la moyenne des températures $\theta_{\text{W,rm}}$;

$P_{\text{LL,rr}} = \left(P_{\text{D,rr}} - P_{0,\text{rr}}\right) - \left(P_{1,\text{rr}} - P_{\text{LL,rm}} - \left(3 \times I^2 \times R_{\text{s,rr}}\right)\right)$ correspond aux pertes aux fréquences plus élevées

où

$R_{\text{s,rr}}$ est la résistance de phase du stator rapportée à la moyenne des températures $\theta_{\text{W,rr}}$.

Les pertes supplémentaires en charge à un point de fonctionnement spécifié peuvent être déterminées par les étapes suivantes.

a) Calculer une valeur approximative pour le courant de charge assigné I_{NL} qui correspond à la valeur assignée du courant de ligne du stator:

$$I_{\text{NL}} = \sqrt{I_{\text{N}}^2 - I_0^2} \quad (44)$$

où

I_{N} est la valeur assignée du courant de ligne du stator;

I_0 est la valeur du courant à vide du stator.

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