IEC TS 62898-3-3

Edition 1.0 2023-08

TECHNICAL SPECIFICATION

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Microgrids –
Part 3-3: Technical requirements – Self-regulation of dispatchable loads

IEC TS 62898-3-3:2023-08(en)

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INTERNATIONAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

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IEC TS 62898-3-3 has been prepared by subcommittee SC 8B: Decentralized electrical energy systems, of IEC technical committee TC 8: System aspects of electrical energy supply. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
8B/155/DTS	8B/172/RVDTS

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 Technical Specification 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/standardsdev/publications.

A list of all parts in the IEC 62898 series, published under the general title *Microgrids*, 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- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Self-regulation of loads is a phenomenon known very well to transmission system operators, see Annex A. This effect historically emerged from the dynamic behaviour of electric motors that were used to directly power mechanical drivetrains, for example for pumps or air blowers. The higher the rotational speed of the drive, the more active power is used and vice versa. This effect automatically contributes to frequency stabilization without a supervisory control.

There is also a self-regulation effect on the voltage due to resistive loads. At higher voltages, the current through a resistive load increases and therefore the active power consumption increases as well. This increased current also flows through the impedance of the upstream supply network, resulting in a voltage reduction at the load's point of connection and vice versa. This effect helps to stabilise the voltage and is also used indirectly with power system stabilisers (PSS). Modulated system voltage at transmission level is translated to corresponding changes of active power consumption of loads at distribution level which dampen low frequency power oscillations.

This document intends to emulate the above explained beneficial behaviours with dispatchable loads, which do not affect the functionality with regard to the end user, and to make this effect available for frequency and voltage stabilization in microgrids. Dispatchable loads can modify the active power consumption while maintaining their functionality by keeping system parameters within acceptable ranges. This is usually achieved by the use of an internal energy storage, for example thermal energy storage in refrigerators, freezers, air conditioners, water heaters, or electrical energy storage units such as batteries. As the loads respond to the frequency and voltage they experience, no communication channels or complex control systems are necessary to include small loads in the common task of keeping the electric system stable.

MICROGRIDS –

Part 3-3: Technical requirements – Self-regulation of dispatchable loads

1 Scope

This part of IEC 62898 deals with frequency and voltage stabilization of AC microgrids by dispatchable loads, which react autonomously on variations of frequency and voltage with a change in active power consumption. Both 50 Hz and 60 Hz electric power systems are covered. This document gives requirements to emulate the self-regulation effect of loads including synthetic inertia.

The loads recommended for this approach are noncritical loads, this means their power modulation will not significantly affect the user as some kind of energy storage is involved which effectively decouples end energy use from the electricity supply by the electric network. The self-regulation of loads is beneficial both in island mode and grid-connected mode. This document gives the details of the self-regulation behaviour but does not stipulate which loads shall participate in this approach as an optional function.

This document covers both continuously controllable loads with droop control and ON/OFF-switchable loads with staged settings. The scope of this document is limited to loads connected to the voltage level up to 35 kV. Reactive power for voltage stabilization and DC microgrids are excluded in this document.

NOTE 1 If agreed between system operator and grid user, the self-regulating principles outlined in this document can also be applied to loads in other electricity networks, see IEC/ISO Directives, Part 1:2023, C.4.3.2, Example 1.

NOTE 2 According to 3.1.7, critical loads with an electrical energy storage system such as an uninterruptable power supply are considered as noncritical and therefore dispatchable.

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.

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

3 Terms, definitions, abbreviated terms and symbols

For the purposes of this document, the following terms, definitions and abbreviated apply.

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

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

3.1 Terms and definitions

3.1.1
accuracy
<of a measuring instrument> quality which characterizes the ability of a measuring instrument to provide an indicated value close to a true value of the measurand

Note 1 to entry: This term is used in the "true value" approach. An updated term using the "uncertainty" approach is in preparation for edition 2 of this document.

Note 2 to entry: Accuracy is all the better when the indicated value is closer to the corresponding true value.

[SOURCE: IEC 60050-311:2001, 311-06-08, modified – Note 1 to entry has been expanded.]

3.1.2
closed-loop control
process whereby one variable quantity, namely the controlled variable is continuously or sequentially measured, compared with another variable quantity, namely the reference variable, and influenced in such a manner as to adjust to the reference variable

Note 1 to entry: Characteristic for closed-loop control is the closed action in which the controlled variable continuously or sequentially influences itself in the action path of the closed loop.

[SOURCE: IEC 60050-351:2013, 351-47-01, modified – Note 2 to entry has been deleted.]

3.1.3
control loop
set of elements or systems incorporated in the closed action of a closed-loop control

[SOURCE: IEC 60050-351:2013, 351-47-11, modified – Note 1 to entry has been deleted.]

3.1.4
damping coefficient
δ
positive quantity δ in the expression $A_0 e^{-\delta t} f(x)$ of an exponentially damped oscillation, where $f(x)$ is a periodic function

[SOURCE: IEC 60050-103:2009, 103-05-24]

3.1.5
damping ratio
for a linear time-invariant system described by the second order differential equation

$$\frac{d^2 x}{dt^2} + 2 \cdot \vartheta \cdot \omega_0 \cdot \frac{dx}{dt} + \omega_0^2 \cdot x = 0$$

the value of the coefficient ϑ,

where

t is the time;

x is a state variable of the system;

ω_0 is the characteristic angular frequency of the system

Note 1 to entry: When ϑ<1, $\omega_d = \omega_0 \cdot \sqrt{1-\vartheta^2}$ is the eigen angular frequency of the system.

[SOURCE: IEC 60050-351:2013, 351-45-19, modified – Note 2 to entry has been deleted.]

3.1.6
dead band
dead zone
finite range of values of the input variable within which a variation of the input variable does not produce any measurable change in the output variable

Note 1 to entry: When this type of characteristic is intentional, it is sometimes called neutral zone.

[SOURCE: IEC 60050-351:2013, 351-45-15, modified – Note 2 to entry has been deleted.]

3.1.7
dispatchable load
noncritical load
load for which the active power consumption can be modified while maintaining the functionality of that load within an acceptable range of parameters

Note 1 to entry: Maintaining the load's functionality is often achieved by use of an internal energy storage.

Note 2 to entry: The use of dispatchability depends on an agreement between grid user and grid operator.

Note 3 to entry: The feature of dispatchability can be made accessible either by self-regulation or remote control.

Note 4 to entry: The reference point for the conformity assessment is the terminal of the load.

3.1.8
droop control
<of dispatchable loads> control loop to control dispatchable loads in such a way that the active power consumption is a function of system frequency, voltage, or both

3.1.9
(electric) island
part of an electric power system that is electrically disconnected from the remainder of the interconnected electric power system but remains energized from the local electric power sources

Note 1 to entry: An electric island can be either the result of the action of automatic protections or the result of a deliberate action.

Note 2 to entry: An electric island can be stable or unstable.

Note 3 to entry: Electric islands can be nested.

[SOURCE: IEC 60050-692:2017, 692-02-11, modified – Note 3 to entry has been added.]

3.1.10
fault ride through
FRT
ability of a load to stay connected during specified faults in the electric power system

3.1.11
(frequency) droop
ratio of the per-unit changes in frequency $(\Delta f)/f_n$ (where f_n is the nominal frequency) to the per-unit change in power $(\Delta P)/P_{ref}$ (where P_{ref} is the reference active power):

$$\sigma = (\Delta f/f_n) / (\Delta P/P_{ref})$$

Note 1 to entry: Frequency droop is f-by-P, whereas the often used characteristic curve is $P(f)$.

Note 2 to entry: The reference active power P_{ref} is either the nominal active power or the present active power.

Note 3 to entry: The same principle can be applied for a voltage droop.

Note 4 to entry: The frequency gradient of a characteristic curve, which describes the power response to frequency, is the active power change per frequency change. In a 50 Hz system, a droop of σ % can be transformed into a gradient g % (in P_n/Hz) by the formula $g = 200/\sigma$; in a 60 Hz system $g = 166{,}7/\sigma$.

[SOURCE: IEC 60050-603:1986, 603-04-08, modified – The notes have been added, the nominal power has been replaced with reference power, and the specific use <of a set> has been deleted in the term.]

3.1.12
frequency response
for a linear time-invariant system with a sinusoidal input variable in steady state of the output variable the ratio of the phasor of the output variable to the phasor of the corresponding input variable, represented as a function of the angular frequency ω

Note 1 to entry: The frequency response coincides with the transfer function taken on the imaginary axis of the complex plane.

[SOURCE: IEC 60050-351:2013, 351-45-41, modified – Figure 9, Figure 10 and Note 2 to entry have been deleted.]

3.1.13
functional diagram
symbolic representation of the actions in a system by functional blocks, summing points and branching points linked by action lines

Note 1 to entry: The action lines do not necessarily represent physical connections, like electrical wires.

Note 2 to entry: Functional blocks, action lines, summing points, and branching points are elements of the functional diagram.

[SOURCE: IEC 60050-351:2013, 351-44-01, modified – Figure 1, Figure 2 and Note 3 to entry have been deleted.]

3.1.14
hysteresis
phenomenon represented by a characteristic curve which has a branch, called ascending branch, for increasing values of the input variable, and a different branch, called descending branch, for decreasing values of the input variable

SEE: Figure 1.

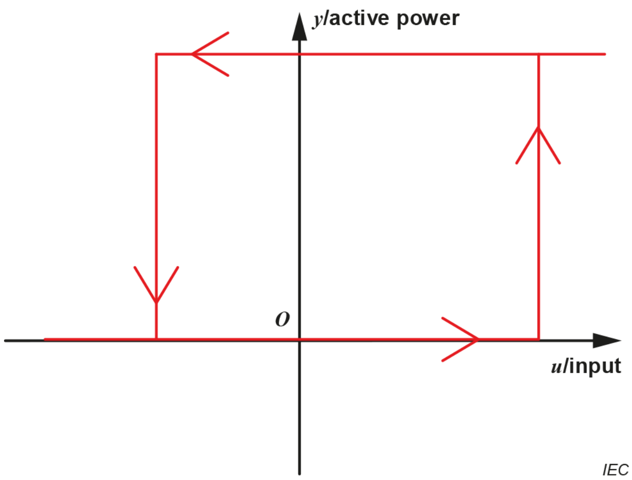


Figure 1 – Hysteresis curve of a switchable load

[SOURCE: IEC 60050-351:2013, 351-45-16, modified – The figure has been added and Note 1 to entry has been deleted.]

3.1.15
hysteresis control
two-state control
control scheme where a device is switched ON when an input variable crosses a threshold value in a given direction, and is switched OFF when the input variable crosses another threshold value in the opposite direction

3.1.16
(hysteresis) width
<of hysteresis control> difference of the input variable between the ON and OFF switching states

3.1.17
immunity
<to a disturbance> ability of a device, equipment or system to perform without degradation in the presence of a voltage or frequency disturbance

3.1.18
inertia,
<in an electric power system> property of a rotating rigid body according to which it maintains its angular velocity in an inertial frame in the absence of an external torque

[SOURCE: IEC 60050-113:2011, 113-03-02, modified – The definition has been modified for the purpose of rotating reference system.]

3.1.19
inertia constant, <of a rotational energy storage>
H
ratio of rotational energy stored at nominal frequency and the nominal power

$H = E_{max} / P_n$

Note 1 to entry: The inertia constant H is half the mechanical starting time T_m.

3.1.20
low-pass filter
filter having a single pass band below a cut-off frequency and a stop band for higher frequencies

[SOURCE: IEC 60050-561:2014, 561-02-26, modified – Note 1 to entry has been deleted.]

3.1.21
measurand
particular quantity subject to measurement

[SOURCE: IEC 60050-311:2001, 311-01-03]

3.1.22
mechanical starting time, <of a rotating electric machine>
T_m
time of a rotating mass from standstill to nominal frequency while being accelerated with nominal torque

Note 1 to entry: The mechanical starting time T_m is twice the inertia constant H.

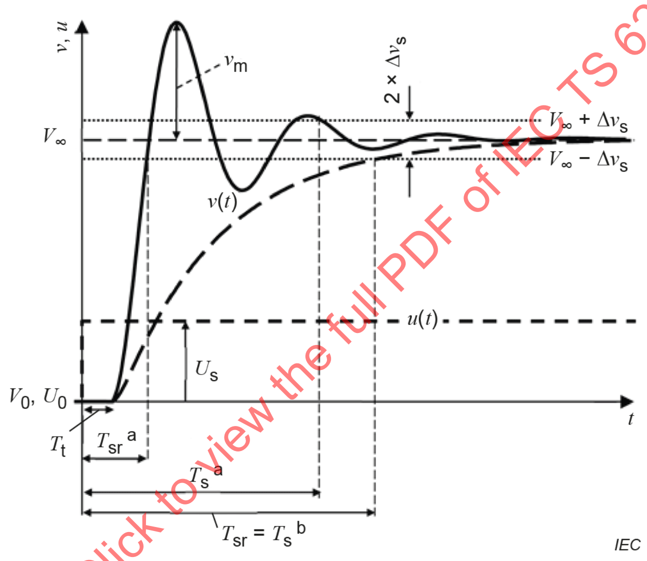
3.1.23
microgrid
<in an electric power system> group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is able to operate in island mode

Note 1 to entry: This definition covers both (utility) distribution microgrids and (customer owned) facility microgrids.

[SOURCE: IEC 60050-617:2017, 617-04-22, modified – Reworded to avoid redundancy.]

3.1.24
overshoot
v_m
for a step response of a transfer element the maximum transient deviation from the final steady-state value of the output variable, mostly used in the form of overshoot ratio

SEE Figure 2 (v_m)



u	Input variable
U_0	Initial value of the input variable
U_s	Step height of the input variable
v	Output variable
V_0, V_∞	Steady-state value before and after application of the step
v_m	Overshoot (maximum transient deviation from the final steady-state value)
$2 \cdot \Delta v_s$	Specified tolerance limit
T_{sr}	Step response time
T_s	Settling time
T_t	Dead time

Figure 2 – Typical step response of a system

[SOURCE: IEC 60050-351:2013, 351-45-38, modified – The second part of the definition has been simplified and adapted to the purpose of this document.]

3.1.25
overshoot ratio
ratio between the overshoot and the difference of steady-state values before and after the application of the step

$$v_{\mathrm{m}} / (V_{\infty} - V_0)$$

3.1.26
over-voltage ride through
OVRT
ability of a load to stay connected during a limited duration rise of system voltage

3.1.27
power system stability
capability of a power system to regain a steady state, characterized by the synchronous operation of the generators after a disturbance due, for example, to variation of power or impedance

[SOURCE: IEC 60050-603:1986, 603-03-01]

3.1.28
primary control
<for active power> control of generators or loads by their individual controllers which ensures that the active power flow is a function of the power frequency or network voltage

3.1.29
rebound effect
aggregated increase or decrease of power consumption after synchronised demand response deactivation

Note 1 to entry: The risk of oscillating rebound effects is small when there is a high diversity in the time constants of the relevant dispatchable loads, which define the need to switch from on to off and vice versa.

3.1.30
resolution
smallest change in the measurand, or quantity supplied, which causes a perceptible change in the indication

[SOURCE: IEC 60050-311:2001, 311-03-10]

3.1.31
rate of change of frequency
ROCOF
first-order derivative in time of the frequency

$$\mathrm{d}f/\mathrm{d}t$$

3.1.32
secondary control
<of active power in a system> coordinated control of the active power supplied to the network by particular generators

Note 1 to entry: The secondary control usually has an integrative component to ensure steady state accuracy of the controlled variable.

[SOURCE: IEC 60050-603:1986, 603-04-05, modified – Note 1 to entry has been added.]

3.1.33
self-regulation
<of loads> inherent feature of loads to react under certain conditions autonomously on variations of frequency or voltage or both with a change in the power exchange with the electric power network

Note 1 to entry: In this document active power is considered only, $Q(U)$ is not covered.

3.1.34
simulated electric power system interface
grid simulator
SEPSI
assembly of test equipment with variable voltage and variable frequency output emulating a power system at the point of connection

Note 1 to entry: Normally, a SEPSI is voltage source converter with AC/DC/AC structure.

3.1.35
state of energy
SOE
ratio between the currently stored energy from an energy storage at specified operational conditions and the maximum storable energy when fully charged, typically expressed as a percentage

Note 1 to entry: Stored energy is the energy which is physically contained in an energy storage. The stored energy is independent of the charge or discharge power.

[SOURCE: IEC 62933-1:2018, 3.2.4, modified – In the term, “charge” has been changed to “energy”, the definition now comprises all kinds of energy storage and Note 1 to entry has been added.]

3.1.36
step response
time response of a linear time-invariant system, which initially is in steady state U_0, V_0, produced by application of a step function $\Delta u_\varepsilon(t) = K_\varepsilon \cdot \varepsilon(t)$ to one of the input variables, where $\Delta v_\varepsilon(t) = v(t) - V_0$ and $\Delta u_\varepsilon(t) = u(t) - U_0$

Note 1 to entry: The step response of a linear time-invariant system is proportional to the time integral of its impulse response.

[SOURCE: IEC 60050-351:2013, 351-45-27, modified – Figure 5 and Note 2 to entry have been deleted.]

3.1.37
step response time
for a step response the duration of the time interval between the instant of the step change of an input variable and the instant when the output variable reaches for the first time a specified percentage of the difference between the final and the initial steady-state value

SEE Figure 2 (T_{sr}).

Note 1 to entry: In the case of PT1-behaviour of a first order low-pass filter with a transfer function K / (1+T_s), the output variable reaches 0,95 of the difference between the final and the initial steady-state value after 3 τ. Therefore, the bandwidth of ± 5 % is an often-used bandwidth around the targeted value.

[SOURCE: IEC 60050-351:2013, 351-45-36, modified – The original note has been deleted and Note 1 to entry has been added.]

3.1.38
synchronisation
<of dispatchable loads> aggregated response of different dispatchable loads within a synchronous area by simultaneously switching on or off so that the adjustments of their active power consumption coincide with each other

Note 1 to entry: Synchronisation of dispatchable loads can contribute to frequency instability.

Note 2 to entry: Desynchronisation of dispatchable loads refers to the practice of avoiding synchronisation in the electric power system.

3.1.39
synthetic inertia
<in an electric power system> capability of a grid connected converter to emulate the effect of inertia of a synchronous generator to a prescribed level of performance

3.1.40
time response
variation in time of an output variable, produced by a specified variation of one of the input variables, under specified operating conditions

[SOURCE: IEC 60050-351:2013, 351-45-09, modified – Note 1 to entry has been deleted.]

3.1.41
torque
component of a moment of force M along a given axis passing through the origin point, thus $T = M \cdot e$, where e is the unit vector of the axis

Note 1 to entry: Torque is the twisting moment of force with respect to the longitudinal axis of a beam or shaft.

[SOURCE: IEC 60050-113:2011, 113-03-26, modified – The note to entry was reformatted.]

3.1.42
transfer function
for a linear time-invariant system the ratio of the Laplace transform of an output variable to the Laplace transform of the corresponding input variable, with all initial values equal to zero

[SOURCE: IEC 60050-351:2013, 351-45-39, modified – Note 1 to entry has been deleted.]

3.1.43
uncertainty
<of a measurement> parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

Note 1 to entry: This term is used in the "uncertainty" approach.

Note 2 to entry: The parameter can be, for example, a standard deviation (or a given multiple of it), or a half-width of an interval having a stated level of confidence. Various ways of obtaining uncertainty are defined in ISO/IEC Guide 98.3, Guide to the expression of uncertainty in measurement (GUM).

Note 3 to entry: Uncertainty of measurement comprises, in general, many components. Some of these components can be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from the assumed probability distributions based on experience or other information.

[SOURCE: IEC 60050-311:2001, 311-01-02, modified – The notes are reformatted, and GUM in Note 2 to entry is written in full.]

3.1.44
under-voltage ride through
UVRT
ability of a load to stay connected during a voltage dip

Note 1 to entry: In some documents the term “low voltage ride through (LVRT)”, is used for the same capability.

Note 2 to entry: As a synonym for voltage dip, voltage sag is also used.

3.1.45
voltage dip
voltage sag
sudden voltage reduction at a point in an electric power system, followed by voltage recovery after a short time interval, from a few periods of the sinusoidal wave of the voltage to a few seconds

[SOURCE: IEC 60050-614:2016, 614-01-08]

3.1.46
voltage droop
ratio of the per-unit change in voltage $(\Delta U)/U_\text{n}$ (where U_n is the nominal voltage) to the per-unit change in active power or reactive power

Note 1 to entry: The active power voltage droop is $U(P)$, whereas the often-used characteristic curve is $P(U)$.

Note 2 to entry: The reactive power voltage droop is $U(Q)$, whereas the often-used characteristic curve is $Q(U)$.

3.2 Abbreviated terms and symbols

3.2.1 Abbreviated terms

BIPM	Bureau International des Poids et Mesures
EES	Electrical energy storage
EMS	Energy management systems
ES	Energy storage
EUT	Equipment under test
FRT	Fault ride through
GUM	Guide to the expression of uncertainty in measurement
OVRT	Over-voltage ride through
RMS	Root mean square
ROCOF	Rate of change of frequency
SEPSI	Simulated electric power system interface
SOE	State of energy
THD	Total harmonic distortion
UVRT	Under-voltage ride through

3.2.2 Symbols

f	frequency
H	inertia constant
P	active power
T	torque
T_m	mechanical starting time
T_w	measurement time window
T_s	settling time
T_sr	step response time
T_t	dead time

τ time constant

U voltage

U_0 initial value of the input variable

U_s step height of the input variable

u input variable

v output variable

V_0 steady-state value before application of the step

V_∞ steady-state value after application of the step

v_m overshoot (maximum transient deviation from the final steady-state value)

$2 \cdot \Delta v_s$ specified tolerance limit

4 Requirements on self-regulation

4.1 General

4.1.1 Operational ranges

The purpose of 4.1.1 is to define immunity ranges in which the dispatchable loads shall continue to function as designed to support microgrid stability, notwithstanding intentional disconnecting according to 4.2.3 and 4.3.3 (switchable loads).

NOTE 1 IEC TS 62749 indicates fluctuations of frequency and voltage which can be expected during normal operation of power systems. During exceptional conditions, wider frequency tolerances can be applied temporarily in order to maintain the continuity of electricity supply.

a) Frequency ranges for frequency stabilization:
   1) ±5 % during continuous operation,
   2) ±15 % during short events up to 5 min;

NOTE 2 In dynamic response, power swings are different in electrical islands as well as in weakly connected grids compared to the core of a synchronous zone.

b) Voltage ranges for voltage stabilization:
   1) +10 % or −15 % during continuous operation,
   2) +20 % or −30 % during short events only up to 5 s.

NOTE 3 The wide shall-not-trip area even for a longer time is explained by FRT requirements including UVRT at 70 % U_n and OVRT at 120 % U_n for several seconds.

The values in items a) and b) listed above are recommended as default values. Individual microgrid designs may require different values.

NOTE 4 Within the operational ranges, the control strategies for different loads can be differentiated according to their priorities, see Annex C.

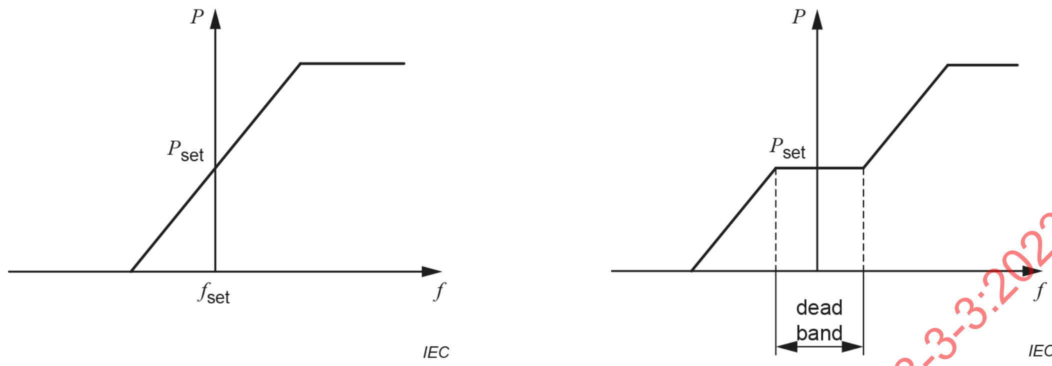
4.1.2 Continuous and discrete control

In the field of digital controllers, the term "continuous" is defined by the sampling frequency, the duration of the control cycle, and other dynamic parameters. In this document, the differentiation between discrete versus continuous refers to frequency and voltage measurement at input level.

In this document the differentiation between continuously controllable versus switchable loads concerns mainly the output level, i.e. gradual power modulation versus ON/OFF.

4.1.3 Dead band

A dead band should be activated only after a risk-benefit evaluation. The default is to have the dead band deactivated. An example of a dead band is given in Figure 3.



a) without dead band

b) with dead band

Figure 3 – Example of $P(f)$ self-regulation before and after activating the dead band

4.1.4 Accuracy and resolution

Frequency measurement accuracy shall be at least ±50 mHz, as shown in Table 1. The frequency measurement shall be performed on a measurement time window with a maximum length of T_w = 1 s and the measurement window shall be coordinated with the time quality levels of Table 3. The manufacturer shall declare the accuracy level depending on the targeted time domain as given in Table 3.

NOTE 1 Measurement sampling frequency (used by A/D and D/A converters) and calculation methods are up to the manufacturer.

Table 1 – Declared frequency measurement accuracy levels

Level	**Accuracy level** mHz
FQ1	± 1
FQ2	± 10
FQ3	± 50
NOTE Examples for frequency measurement requirements in protection relays, primary control and secondary control are given in EN 50549-1:2019 [18][1], 4.9.3, or system operation guideline Regulation (EU) 2017/1485 [17], Article 130 and Annex V.	

The quality of the frequency measurement equipment should ensure that the required levels of measurement accuracy in Table 1 are attained, considering all sources of uncertainty in the measurement process.

Voltage measurement accuracy shall be at least ±1 % of U_n, shown in Table 2. The manufacturer shall declare the accuracy level depending on the time domain as given in Table 3.

[1] Numbers in square brackets refer to the Bibliography.

Table 2 – Declared voltage measurement accuracy levels

Level	Accuracy level
VQ1	±0,1 % U_n
VQ2	±0,25 % U_n
VQ3	±1 % U_n
NOTE 1 Examples for voltage measurement requirements in protection relays are given in EN 50549-1:2019 [18], 4.9.3. NOTE 2 Voltage measurements are represented by the RMS value of the voltage signal. NOTE 3 The higher the accuracy of frequency and voltage measurement, the better the behaviour of the load is in principle, other things held constant.	

The accuracy levels above are to be translated in output accuracies (active power) according to the gradient of the relevant k factor of the droop.

NOTE 2 The relationship between measurement accuracy and the active power output accuracy is determined by the slope of the characteristic curve. For example, a $P(f)$ gradient of 40 %/Hz connects the input accuracy (frequency measurement accuracy) of ±50 mHz with an output accuracy of ±2 % of the reference power, whereas a gradient of 100 %/Hz relates a ±10 mHz measurement accuracy to an output accuracy of 1 % of the reference power.

4.1.5 Step response objective

The general principle is to pursue a satisfactory dynamic performance, i.e., to avoid any large delay or overshoot. Shorter step response times are hence preferred in general. However, in case that a load requires time to change its level of active power consumption, Table 3 gives a series of common step response times T_{sr} and associated settling times T_s (specified tolerance band delta v_s of 5 %) in ascending order of merit.

Table 3 – Time quality levels

Level	Step response times (primary condition)	Settling times (secondary condition)	Comparable service
TQ1	3 cycles	10 s	For example very fast current control
TQ2	200 ms	10 s	For example fast current control
TQ3	1 s	10 s	For example signalled load shedding
TQ4	30 s	10 s	For example primary frequency control
TQ5	5 min	10 s	For example secondary frequency control
TQ6	15 min	10 s	For example tertiary frequency control

The dynamic performance ratio is measured as overshoot ratio with the overshoot divided by the difference between steady-state values before and after the step response, shown in Table 4.

Table 4 – Performance quality levels

Level	Performance quality as overshoot ratio with 2 decimals	Damping ratio	Description
PQ0	Overshoot ratio $\leq$ 0	~0,707	Critically damped (aperiodic limit case)
PQ1	Overshoot ratio $\leq$ 0,1	~0,54	Excellent
PQ2	Overshoot ratio $\leq$ 0,15	~0,5	Very good (typical value)
PQ3	Overshoot ratio $\leq$ 0,2	~0,47	Good
PQ4	Overshoot ratio $\leq$ 0,3	~0,425	Acceptable

4.1.6 Damping

Power system dynamics can be approximated in a simplified case with a second order ordinary differential equation:

$$\ddot{x}(t) + 2\vartheta\omega_0\dot{x}(t) + \omega_0^2 x(t) = 0 \qquad (1)$$

where

ϑ is the damping ratio;

ω_0 is the characteristic angular frequency;

x is the controlled system variable.

A damping ratio of ϑ = $\sqrt{2}/2$ for a load results in an overshoot ratio of less than 5 %. Acceptable ranges for damping ratio are within a bandwidth of −10 % and +5 % of this value. More information on damping is given in Annex D.

During the conformity assessment for the different performance quality levels in accordance with Table 4, the overshoot ratio, which gives an estimate of the resulting damping coefficient, is determined.

4.2 Frequency stabilization

4.2.1 General

Frequency stabilization by dispatchable loads is achieved through a frequency-sensitive control mode ($P(f)$ load regulation) of the load's controller, where the dispatchable load will adjust its active power consumption level in response to a change in power frequency. The load increases its active power consumption at higher frequency or positive ROCOF and decreases its power consumption at lower frequency or negative ROCOF. The objective of this self-regulation is to contain nominal frequency without major deviations and to improve frequency quality.

This approach emulates the known behaviour of a constant torque rotating electric machine which is directly connected to the electric power system. It avoids the $P(f)$ = const behaviour of some loads, for example inverter-controlled drives, as this $P(f)$ = const control strategy is responsible for the degradation of the self-regulation effect.

4.2.2 Continuously controllable loads

4.2.2.1 *P*(*f*) control function components

4.2.2.1.1 General

The *P*(*f*) control function consists of different components as described below and which are added together in the combined function of 4.2.2.2. Each component of the combined function can be fine-tuned via the *k*-parameters or disabled by choosing $k = 0$.

4.2.2.1.2 Frequency response with proportional droop (proportional-component)

The proportional-component uses a droop function based on the idea to emulate a constant torque. The quality levels of the dynamic behaviour for step response time and performance quality (overshoot ratio) are given in 4.2.3.

The *P*(*f*) control function based on the emulation of constant torque is formulated as Formula (2) and Formula (3):

$$P(f) = P_{\text{set}} + \Delta P(f) \tag{2}$$

$$\Delta P(f) = P_{\text{set}} \cdot k_{\text{1c,f}} \cdot (f - f_{\text{set}}) \tag{3}$$

P_{set} is the power setpoint of the dispatchable load, set directly by the user or via an energy management system (EMS). $k_{\text{1c,f}}$ is the gradient in %/Hz of the power setpoint. For the choice of gradient $k_{\text{1c,f}}$, see Annex B. A development of Formula (3) is theoretically explained in Annex E.

4.2.2.1.3 Frequency response being proportional to d*f*/d*t* (derivative-component)

The derivative-component delivers synthetic inertia by emulating inertia with a mechanical starting time T_{m} two times the inertia constant H ($T_{\text{m}} = 2H$). As the differential amplifies high frequency noise (see the Bode diagram in Figure 4), an input filter is necessary for compensation and to level out the noise above a certain cut-off frequency. It is recommended to use for the angular speed of the grid phasor a first order low pass with τ = 10 ms as default value and with settings possible within the interval from 2 ms to 100 ms.

NOTE 1 The cut-off frequency $f_{\text{cut-off}}$ for a first order low pass with the transfer function $1/(\tau s+1)$ equals $1/\tau$.

NOTE 2 A PT1 filter is after 1 time constant τ at 63 % and after 3 τ at 95 % of the final value.

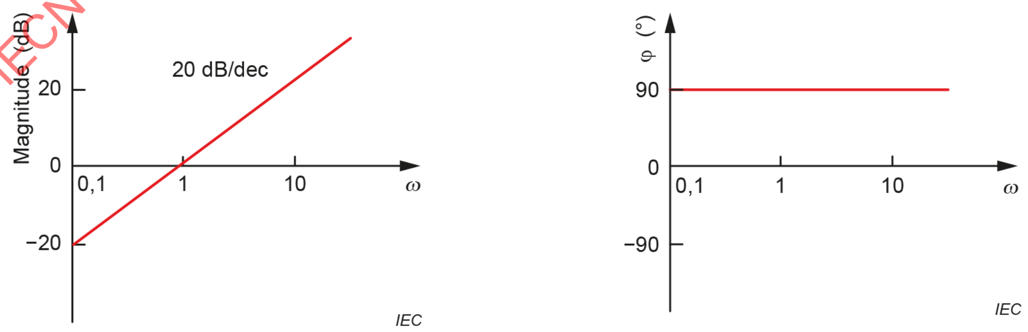
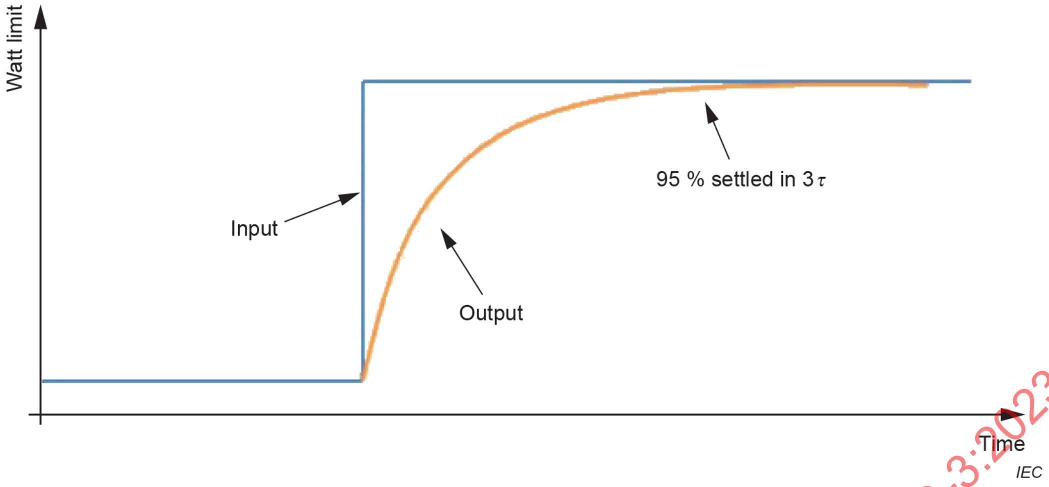


Figure 4 – Bode diagram of a typical differential loop



[SOURCE: IEC TR 61850-90-7:2013, Figure 12.]

Figure 5 – Time domain response of first order low-pass filter

The derivative-component is formulated as Formula (2) and Formula (4).

$$\Delta P = P_{\text{set}} \cdot k_{3\text{c,f}} \cdot \frac{\text{d}f}{\text{d}t} \tag{4}$$

where $k_{3\text{c,f}}$ is the gradient in %/s^{-2}.

4.2.2.2 Combined function

The function formulated as Formula (5) uses P_{set} as given setpoint by the user or EMS and modulates this set value according to the frequency measurements. The relevant functional diagram is provided in Figure 6.

$$P(f) = P_{\text{set}} + \Delta P(f) = P_{\text{set}} \cdot \left[1 + k_{1\text{c,f}} \cdot (f - f_{\text{set}}) + k_{3\text{c,f}} \cdot \frac{\text{d}f}{\text{d}t}\right] \tag{5}$$

$k_{1\text{c,f}}$ or $k_{3\text{c,f}}$ = 0 means that the function is disabled. Ranges and default values for the k-parameters are given in 4.2.4.

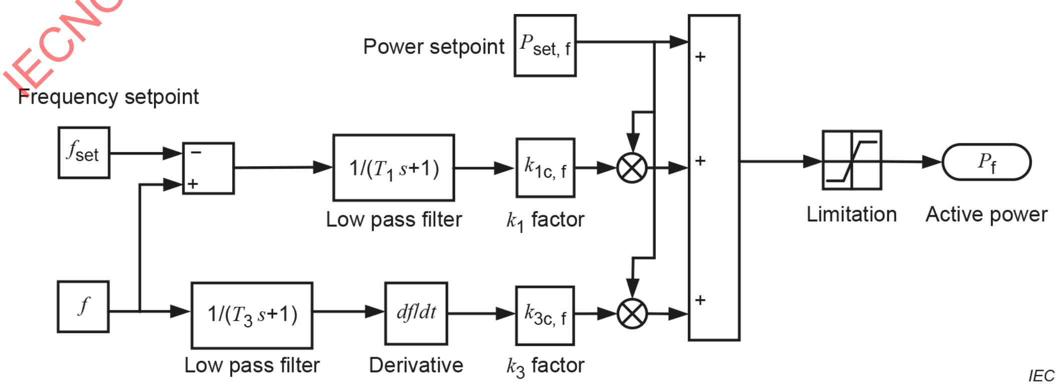


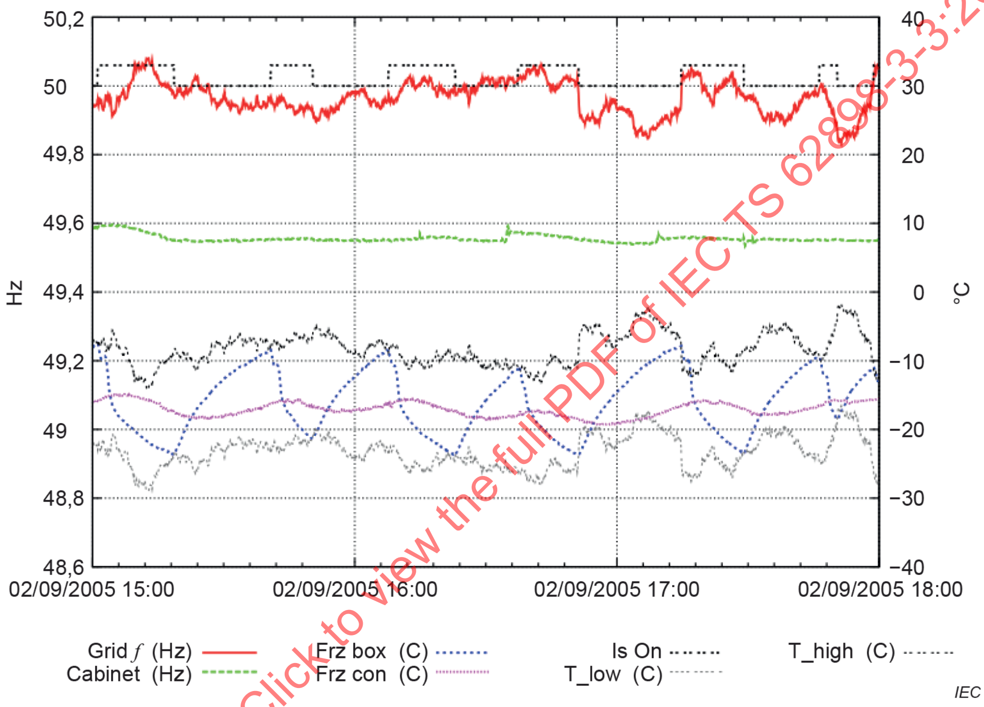
Figure 6 – Functional diagram of a combined frequency control function for continuously controllable dispatchable loads

4.2.3 Switchable loads

4.2.3.1 Digital hysteresis controller

A cluster of dispatchable loads where the individual load follows a staged disconnection and staged reconnection does emulate droop characteristics. The switching from one state to another depends on an internal system state (e.g. temperature as an indicator for the state of charge of an internal thermal energy storage) and the measured grid frequency.

The setpoint is the desired internal state (e.g. temperature level or SOE), and the ON-OFF hysteresis shifts the switching thresholds of the two-state controller upwards and downwards respectively. An example of a hysteresis controller used in grid frequency regulation is illustrated in Figure 7.



[SOURCE: Reproduced from [26], with the permission of the author.]

Figure 7 – Example of a hysteresis controller to control the temperature of a freezer in response to variations in grid frequency

The function of a hysteresis controller is formulated as Formula (6) and Formula (7).

$$\mathrm{ON_{threshold}} = \mathrm{setpoint} - \frac{1}{2}\mathrm{hysteresis_{width}} \tag{6}$$

$$\mathrm{OFF_{threshold}} = \mathrm{setpoint} + \frac{1}{2}\mathrm{hysteresis_{width}} \tag{7}$$

NOTE Here, the ON state means that the energy storage is charged (e.g. an electric boiler heats up or a fridge cools down).

EXAMPLE With a temperature-controlled device in form of an electric boiler, having a setpoint of 55 °C and a width of the hysteresis of 10 °C, the ON threshold would be 50 °C and the OFF threshold would be 60 °C, as the thermal energy storage is charged when water is heated up and discharged when it cools down.

In order to avoid oscillations caused by synchronisation of switchable loads after a major frequency or voltage deviation, it should be ensured that the aggregated response of loads is always in a dispersed manner, so that a synchronised group of loads quickly diverges and rebound effects are minimized.

This can be achieved by several possible approaches, for example by adding non-deterministic elements in the load's control structure, increasing the heterogeneity of different loads, or converting the ON-OFF hysteresis into a kind of long-duration pulse width modulation. Annex F provides more information.

For conformity assessment, a computer simulation should be carried out to examine the cluster behaviour of multiple loads after being activated for frequency or voltage regulation. The expected behaviour is that the cluster disperses more quickly after being partly synchronised and does not escalate into a synchronised oscillation.

4.2.3.2 Combined function

The combined function of different controller logic components similar to 4.2.2.2 is formulated as Formula (8) and Formula (9).

$$\mathrm{ON}_{\mathrm{threshold}} = \mathrm{setpoint} - \frac{1}{2}\mathrm{hysteresis}_{\mathrm{width}} + k_{1\mathrm{s,f}} \cdot (f - f_{\mathrm{set}}) + k_{3\mathrm{s,f}} \cdot \frac{\mathrm{d}f}{\mathrm{d}t} \tag{8}$$

$$\mathrm{OFF}_{\mathrm{threshold}} = \mathrm{setpoint} + \frac{1}{2}\mathrm{hysteresis}_{\mathrm{width}} + k_{1\mathrm{s,f}} \cdot (f - f_{\mathrm{set}}) + k_{3\mathrm{s,f}} \cdot \frac{\mathrm{d}f}{\mathrm{d}t} \tag{9}$$

NOTE 1 A k factor = zero means that the function is disabled.

NOTE 2 ON/OFF-thresholds refer to indicators (e.g. temperature or the state of energy (SOE)) of an energy storage (ES) serving as functional electrical energy storage (EES). Therefore, these switching levels in the two-state controller and the relevant k factors are different values than the k factors in the continuously controllable mode as there the k factors modify the active power directly.

4.2.4 Recommended default values

The default value for the $k_{1,\mathrm{f}}$ is an equivalent droop of 5 % with a settable range of 2 % to 12 %.

NOTE 1 In a 50 Hz system, a 5 % droop equals a gradient of 40 % of actual power per Hz. In a 60 Hz system, a 5 % droop equals a gradient of 33,3 %/Hz. In both cases, the full power is activated or deactivated at ±5 % of the nominal frequency.

The default value for the $k_{3,\mathrm{f}}$ is the ratio of the mechanical starting time T_{m} and the nominal frequency f_{n}. The default value of the mechanical starting time T_{m} is 10 s (respectively an equivalent inertia constant H = 5 s) and shall have a settable range of 1 s to 30 s.

NOTE 2 Usual nominal frequencies are 16,7 Hz, 50 Hz, 60 Hz and 400 Hz.

NOTE 3 In a 50 Hz electric power system, a mechanical starting time of 10 s results in $k_{3,\mathrm{f}}$ = 10 s / 50 Hz= 0,2 s^2.

4.3 Voltage stabilization

4.3.1 General

Voltage stabilization by dispatchable loads is achieved through a voltage-sensitive control mode ($P(U)$ load regulation) of the load's controller, where the dispatchable load will adjust its active power consumption level in response to a change in system voltage. The load increases its active power consumption at higher voltage and decreases its power consumption at lower voltage. The objective of this self-regulation is to contain nominal voltage without major deviations and to improve voltage quality.

This approach emulates the known behaviour of an ohmic resistor or a constant current source, having a constant or linearly rising current with rising voltage. It avoids the P = const behaviour of some loads as this means a negative differential resistance which is equal to a reduction of effective short circuit power.

4.3.2 Continuously controllable loads

4.3.2.1 *P*(*U*) control function components

4.3.2.1.1 General

The $P(U)$ control function consists of different components as described below and which are added together in the combined function of 4.3.2.2. Each component of the combined function can be fine-tuned via the k-parameters or disabled by choosing $k = 0$.

4.3.2.1.2 Voltage response with proportional droop (proportional-component)

The proportional-component uses a droop function based on the idea to emulate a constant current source or an ohmic resistor. The quality levels of the dynamic behaviour for step response time and performance quality (overshoot ratio) are given in 4.1.5.

The $P(U)$ control function based on the emulation of constant current is formulated as Formula (10) to Formula (12).

$$P(U) = P_{\text{set}} + \Delta P(U) \tag{10}$$

$$I(U) = I_{\text{const}} = P_{\text{set}} \cdot k_{\text{1c,U}} \tag{11}$$

$$\Delta P(U) = I(U) \cdot \Delta U = P_{\text{set}} \cdot k_{\text{1c,U}} \cdot (U - U_{\text{set}}) \tag{12}$$

The $P(U)$ control function based on the emulation of linear current (constant ohmic resistance) is formulated as Formula (10), and Formula (13) to Formula (15).

$$I(U) = \frac{1}{R_{\text{const}}} \cdot U \tag{13}$$

$$P(U) = \frac{1}{R_{\text{const}}} \cdot U^2 \tag{14}$$

$$\begin{aligned} \Delta P(U) &= \frac{1}{R_{\text{const}}} \cdot U^2 - \frac{1}{R_{\text{const}}} \cdot U_{\text{set}}^2 \\ &= \frac{1}{R_{\text{const}}} \cdot \left[2 \cdot U_{\text{set}} \cdot (U - U_{\text{set}}) + (U - U_{\text{set}})^2\right] \\ &= P_{\text{set}} \cdot k_{\text{2c,U}} \cdot \left[2 \cdot U_{\text{set}} \cdot (U - U_{\text{set}}) + (U - U_{\text{set}})^2\right] \end{aligned} \tag{15}$$

P_{set} is the power setpoint of the dispatchable load at nominal voltage, set directly by the user or via an energy management system (EMS). The default value for U_{set} is the nominal voltage U_{n}. The term $P_{\text{set}} \cdot k_{\text{1c,U}}$ resembles a constant current and the term $P_{\text{set}} \cdot k_{\text{2c,U}}$ resembles the conductivity $1/R$. For the choice of gradient $k_{\text{1c,U}}$, see Annex B.

4.3.2.1.3 Voltage response being proportional to d*U*/d*t* (derivative-component)

The derivative-component emulates a capacitor. As the differential amplifies high frequency noise (see the Bode diagram in Figure 4), an input filter is necessary for compensation and to level out the noise above a certain cut-off frequency. It is recommended to use a first order low pass (PT1 filter: $1T$ = 0,63 and $3T$ = 0,95 of the final value) with 1 s as default value and with settings possible within the interval from 1 cycle to 1 h.

The derivative-component is formulated in Formula (16), which combined with Formula (10) forms the full control function.

$$\Delta P(U) = P_{\text{set}} \cdot k_{3\text{c,U}} \cdot \frac{\mathrm{d}U}{\mathrm{d}t} \tag{16}$$

4.3.2.2 Combined function

The function formulated in Formula (17) uses $P_{\text{set,U}}$ as a given setpoint by the user or EMS and modulates this set value according to the voltage measurements. The relevant functional diagram is provided in Figure 8.

$$P(U) = P_{\text{set}} + \Delta P(U) = P_{\text{set}} \cdot \left\{ 1 + k_{1\text{c,U}} \cdot (U - U_{\text{set}}) + k_{2\text{c,U}} \cdot \left[2 \cdot U_{\text{set}} \cdot (U - U_{\text{set}}) + (U - U_{\text{set}})^2 \right] + k_{3\text{c,U}} \cdot \frac{\mathrm{d}U}{dt} \right\} \tag{17}$$

$k_{1\text{c,U}}$, $k_{2\text{c,U}}$ or $k_{3\text{c,U}}$ = 0 means that the function is disabled. Ranges and default values for the k-parameters are given in 4.3.4.

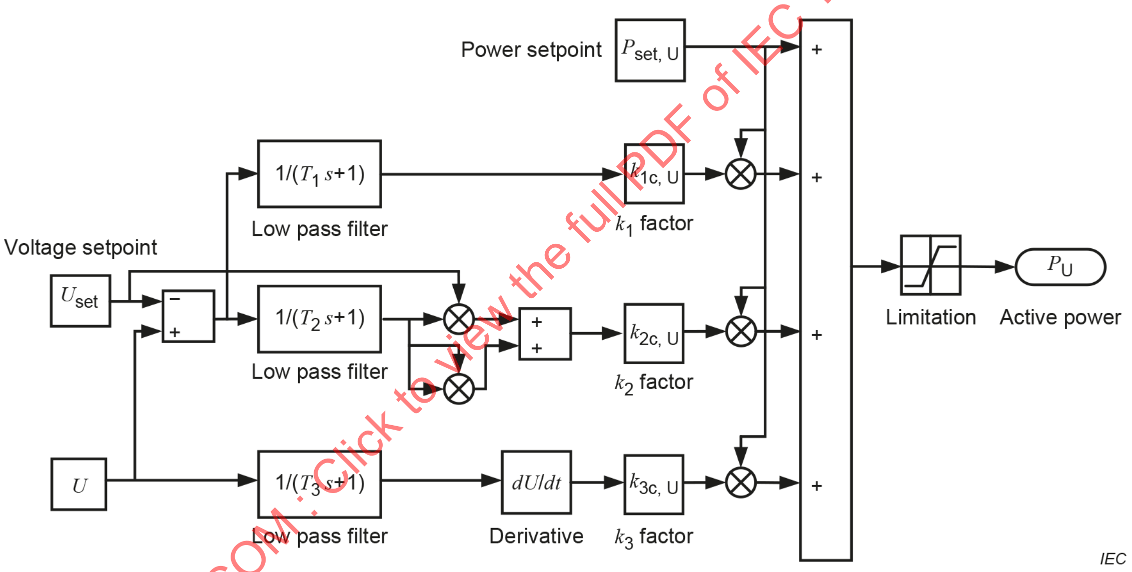


Figure 8 – Functional diagram of a combined voltage control function for continuously controllable dispatchable loads

4.3.3 Switchable loads

4.3.3.1 Digital hysteresis controller

A cluster of dispatchable loads that follows a staged disconnection and staged reconnection does emulate a droop as a whole. The switching from one state to another depends on an internal system state (e.g. temperature as an indicator for the state of charge of an internal thermal energy storage) and the measured network voltage.

The setpoint is the desired internal state (e.g. temperature level or SOE), and the ON-OFF hysteresis shifts the switching thresholds of the two-state controller upwards respectively downwards.

The function of a hysteresis controller is formulated as Formula (18) and Formula (19).

$$ON_{threshold} = setpoint - \frac{1}{2} hysteresis_{width} \quad (18)$$

$$OFF_{threshold} = setpoint + \frac{1}{2} hysteresis_{width} \quad (19)$$

NOTE Here, the ON state means that the energy storage is charged (e.g. an electric boiler heats up or a fridge cools down).

EXAMPLE With a temperature-controlled device in the form of an electric boiler, having a setpoint of 55 °C and a width of the hysteresis of 10 °C, the ON-threshold would be 50 °C and the OFF-threshold would be 60 °C, as the thermal energy storage is charged when water is heated up and discharged when it cools down.

4.3.3.2 Combined function

The combined function of different controller logic components similar to 4.3.2.2 is formulated as Formula (20) and Formula (21).

$$ON_{threshold} = setpoint - \frac{1}{2} hysteresis_{width} + k_{1s,U} \cdot (U - U_{set}) + k_{2s,U} \cdot \left[2 \cdot U_{set} \cdot (U - U_{set}) + (U - U_{set})^2 \right] + k_{3s,U} \cdot \frac{dU}{dt}$$

(20)

$$OFF_{threshold} = setpoint + \frac{1}{2} hysteresis_{width} + k_{1s,U} \cdot (U - U_{set}) + k_{2s,U} \cdot \left[2 \cdot U_{set} \cdot (U - U_{set}) + (U - U_{set})^2 \right] + k_{3s,U} \cdot \frac{dU}{dt}$$

(21)

NOTE 1 A k factor = zero means that the function is disabled.

NOTE 2 ON/OFF-thresholds refer to indicators (e.g. temperature or the state of energy (SOE)) of an energy storage (ES) serving as functional electrical energy storage (EES). Therefore, these switching levels in the two-state controller and the relevant k factors are different values than the k factors in the continuously controllable mode as there the k factors modify the active power directly.

4.3.4 Recommended default values

The chosen default values for the function of stabilization should emulate the characteristic of ohmic resistors.

The self-adjustment for U_{set} and voltage related k factors as adaptive control functions should be done using recent voltage measurements of the near past. The median or alternatively the midhinge of the voltage measurements is recommended as reference for U_{set} while the slope of the droop curve should be derived from the interquartile range as default. Other percentile ranges such as the interdecile range or trimmed ranges down to 5 % should be made configurable.

The adaptive control function shall be activated with weighted average low-pass filter (PT1) with configurable time constant τ, with 3 d as the default value and a settable range from 1 h to 30 d.

4.4 Hybrid controls for both voltage and frequency

Both the frequency stabilising function P_f from 4.2 and the voltage stabilising function P_U from 4.3 and the set value coming from the economic dispatch (EMS) can be added as Formula (22) and Formula (23).

$$P(f,U) = P_{set} + \Delta P(f) + \Delta P(U) \tag{22}$$

$$\begin{aligned} P(f,U) &= P_{set} + k_{1,f} \cdot (f - f_{set}) + k_{3,f} \cdot \frac{df}{dt} \\ &+ k_{1,U} \cdot (U - U_{set}) + k_{2,U} \cdot \left[2 \cdot U_{set} \cdot (U - U_{set}) + (U - U_{set})^2 \right] + k_{3,U} \cdot \frac{dU}{dt} \end{aligned} \tag{23}$$

The related time constants for each of these sub-functions, for example for filtering, the frequency and voltage input values can be different. The synchronisation of the sampling rates should be considered. Both for frequency and voltage the last available RMS value should be used at the reporting moment t.

NOTE Rates for measurement data reporting can be 1 s, 200 ms, or even faster.

5 Testing

5.1 General

The test results shall verify that the equipment under test (EUT) meets the requirements of this document within the manufacturer's specified accuracy. The tests for the conformity assessment serve as type tests. The EUT is the load device, prepared to be tested. The reference point for the conformity assessment is the terminal of the load device.

The manufacturer shall specify the range of operating and ambient conditions (e.g. temperature and humidity) for the EUT. Tests shall be conducted in an environment that is within the manufacturer's specified operating and ambient conditions. EUT functions shall be tested to confirm that they operate within the manufacturer's stated accuracy over the stated range of operating and ambient conditions.

The testing environment shall comply with ISO/IEC 17025. Measurement equipment used to confirm performance of an EUT shall have calibration traceability. The accuracy of the measuring equipment shall be suitable for the test being conducted. Each measurement shall have an uncertainty of no more than 0,5 times the accuracy of the EUT. Measurement equipment shall be capable of confirming the manufacturer's stated performance.

The schematic diagram for the physical test environment of self-regulated load is shown as Figure 9.

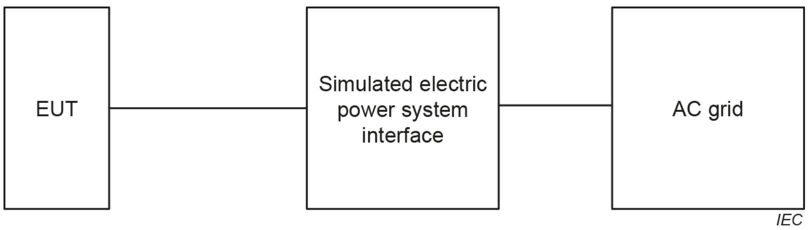


Figure 9 – Schematic diagram for the test environment of a self-regulated load

Where testing allows the use of a simulated electric power system interface (SEPSI), the following requirements shall be met:

1) The SEPSI shall be capable of confirming the manufacturer's stated performance.
2) The rated current and overload capacity of the SEPSI shall cover the whole current range of the EUT.
3) The voltage range of the SEPSI shall cover the whole voltage range required for testing the EUT as described in 4.1.1 b).
4) During the tests, the steady-state voltage of the SEPSI shall not vary by more than ±1 % of the nominal voltage.
5) During the tests, the steady-state frequency of the SEPSI shall not vary by more than ±0,01 Hz.
6) The voltage harmonics of the SEPSI shall be less than 2,5 % total harmonic distortion (THD).
7) For tests checking the voltage response of loads, the voltage change resolution of the SEPSI shall be within 0,5 a of the nominal voltage, where a is the manufacturer's stated accuracy.
8) For tests checking the frequency response of loads, the frequency change resolution of the simulated utility source shall be within 0,5 a of the nominal frequency, where a is the manufacturer's stated accuracy.
9) For tests checking the performance of the EUT, the resolution of active power and the injected frequency or voltage measurement shall be within 0,5 a of the nominal active power, frequency or voltage, where a is the manufacturer's stated accuracy.
10) The number of phase and neutral connections provided by the SEPSI shall be compatible with the EUT. A multiphase SEPSI that provides a neutral connection shall produce phase-to-neutral voltages that are controllable and the possible asymmetry shall cover the full operating range of the EUT. Furthermore, the phase displacement shall be controllable and the possible displacement shall cover the full operating range of the EUT. For a multiphase SEPSI without a neutral connection, the phase-to-phase voltage balance shall be controllable and the possible asymmetry shall cover the full operating range of the EUT.
11) For voltage step change tests, the SEPSI shall be capable of a step change from V_1 to $V_1 + 0,5\ (V_2 - V_1)$ within one cycle of the voltage waveform. For voltage continuous change, the SEPSI shall be capable of voltage continuous change, in which the average error of the voltage continuous change generated by SEPSI compared with the target value should be less than ±1 %.
12) For frequency step change tests, the SEPSI shall be capable of a step change from f_1 to $f_1 + 0,5\ (f_2 - f_1)$ within one cycle of the voltage waveform. For frequency continuous change, the SEPSI shall be capable of frequency continuous change, in which the average error of the frequency continuous change generated by SEPSI compared with the target value should be less than ± 0,01 Hz.

The safety precaution measures for both tester and equipment should be specified before physical test.

During the test, the active demand of the EUT, the frequency and voltage at the terminals of the EUT and the corresponding time should be recorded. The time resolution of the measurement result should be less than or equal to the minimum step response time of the EUT, and should not exceed 10 cycles. Each measurement result should be synchronised with the same time resolution.

The test results shall be documented in a test report. The report shall clearly and unambiguously present all relevant information of the tests (e.g., load conditions, functional description, acceptance criteria, controller or software version if applicable). Within the test report, test procedures, as performed, shall be detailed; and engineering considerations, including test modifications and exemptions, shall be justified.

5.2 Test for frequency response of self-regulated loads

5.2.1 Purpose

The purpose of this test is to verify that the EUT shall make a frequency response function as specified in this document with respect to the frequency variation of SEPSI. This test determines the magnitude and time for each function.

5.2.2 Procedure

1) Connect the EUT according to the instructions and specifications provided by the manufacturer.
2) Set all source parameters to the nominal operating conditions for the EUT.
3) Set (or verify) all EUT parameters to the nominal operating settings.
4) If the frequency response setting is adjustable, set the EUT to the desired frequency response setting.
5) Record the applicable settings.
6) Adjust the SEPSI frequency to the starting point (i.e. nominal frequency). The source shall be held at this frequency for 5 min.
7) Adjust the SEPSI frequency to some over-frequency setpoints with the same time intervals (more than 5 setpoints). At every setpoint, hold for a minimum of 5 s, or, if a longer step response time has been specified by the manufacturer, for at least the settling time. Record the active power and its time marks of the EUT during each setpoint of SEPSI.
8) Adjust the SEPSI frequency to some under-frequency setpoints with the same time intervals (more than 5 setpoints). At every setpoint, hold for a minimum of 5 s, or, if a longer step response time has been specified by the manufacturer, for at least the settling time. Record the active power and its time marks of the EUT during each setpoint of SEPSI.
9) Repeat steps 5) through 8) four times for a total of five tests.
10) If the frequency response setting is adjustable, repeat steps 4) through 9) at every frequency response setting.
11) The overshoot ratio, step response time, average error or gradient of droop control should be calculated via the measurement result.

5.2.3 Criteria

The EUT shall be considered in compliance with the frequency response function specified in this document within the manufacturer's specified accuracy.

5.2.4 Comments

For some EUT, the SEPSI frequency should be changed continuously with certain gradient if its frequency response is proportional to $\mathrm{d}f/\mathrm{d}t$.

For some EUT, the SEPSI frequency should be changed continuously and discretely if its frequency response is a combined function as demonstrated in 4.2.2.2.

5.3 Test for voltage response of self-regulated loads

5.3.1 Purpose

The purpose of this test is to verify that the EUT shall make a voltage response function as specified in this document with respect to the voltage variation of SEPSI. This test determines the magnitude and time for each function.

5.3.2 Procedure

1) Connect the EUT according to the instructions and specifications provided by the manufacturer.

2) Set all source parameters to the nominal operating conditions for the EUT.
3) Set (or verify) all EUT parameters to the nominal operating settings.
4) If the voltage response setting is adjustable, set the EUT to the desired voltage response setting.
5) Record the applicable settings.
6) Adjust the SEPSI voltage to the starting point (i.e. nominal voltage). The source shall be held at this voltage for 5 min.
7) Adjust the SEPSI voltage to some over- voltage setpoints with the same time intervals (more than 5 setpoints). At every setpoint hold for 3 s to 5 s (or for the response time specified by the manufacturer). Record the active power and its time marks of the EUT during each setpoint of SEPSI.
8) Adjust the SEPSI voltage to some under- voltage setpoints with the same time intervals (more than 5 setpoints). At every setpoint hold for 3 s to 5 s (or for the response time specified by the manufacturer). Record the active power and its time marks of the EUT during each setpoint of SEPSI.
9) Repeat steps 5) through 8) four times for a total of five tests.
10) If the voltage response setting is adjustable, repeat steps 4) through 9) at every voltage response setting.
11) The overshoot ratio, step response time, average error or gradient of droop control should be calculated via the measurement result.

5.3.3 Criteria

The EUT shall be considered in compliance with the voltage response function specified in this document within the manufacturer's specified accuracy.

5.3.4 Comments

For some EUT, the SEPSI voltage should be changed continuously with a certain gradient if its voltage response is proportional to dU/dt.

For some EUT, the SEPSI voltage should be changed continuously and discretely if its voltage response is a combined function as demonstrated in 4.3.2.2.

Annex A
(informative)

Background information about the self-regulation effect

Self-regulation of loads is a phenomenon which results from mechanical drives in electric power systems regarding the frequency-dependent consumption of electrical energy. The variable power consumption is not remotely controlled, but an inherent feature of the load itself. The characteristic curve of individual motors and their mechanical subsystems can have different mathematical forms regarding the power consumption in response to RPM changes:

- Falling torque (e.g. coiler, roller press with constant material intake)
  – P is constant.
- Constant torque (e.g. extruder, piston pump, hoisting gear)
  – P is linear.
- Linear rising torque (e.g. calender)
  – P is quadratic.
- Quadratic rising torque (e.g. blower, centrifuge, radial pump, turbo-machine)
  – P is cubic.

Transmission system operators use the self-regulation effect in the case of larger frequency deviations, as this stabilises frequency in the whole operating range and not only in the smaller bandwidth of primary control. A usual conservative assumption to estimate the self-regulation effect is 1 %/Hz. [27] As seen in the example illustrated in Figure A.1 (derived from [27] page A1-7), the self-regulation effect helps to stabilise frequency until primary control is fully deployed. It avoids crossing the frequency threshold which activates the automatic under-frequency load shedding. The self-regulation effect is active in the whole frequency range and has almost no dead-time as frequency response.

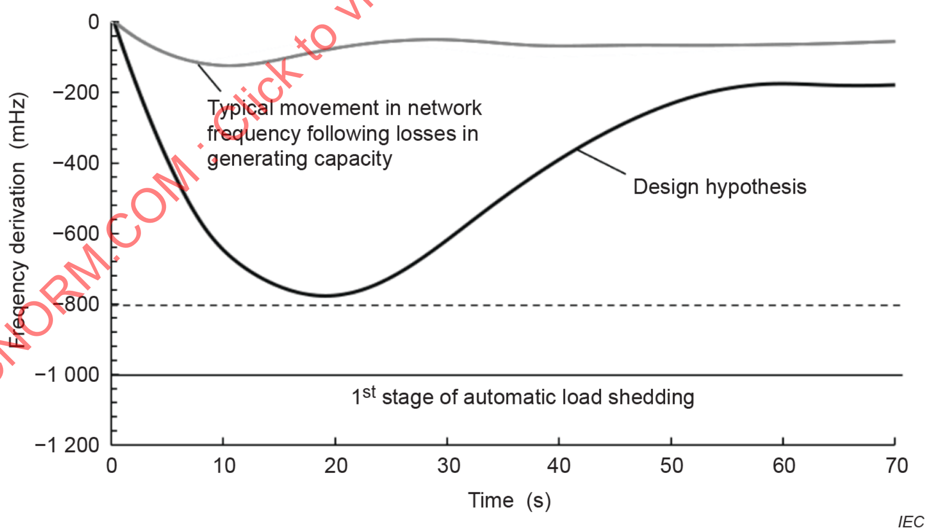


Figure A.1 – Frequency development after a disturbance

Furthermore, there is also a self-regulation effect in the voltage domain which is caused by resistive loads. An ohmic resistance has a linear relation between voltage U and current I, hence its power as a function of voltage is a quadratic term. At higher voltages, the current through a resistive load increases and therefore the active power consumption increases as well. This increased current also flows through the impedance of the upstream supply network, which has at low and medium voltage level a large ohmic characteristic, resulting in a voltage reduction at the load’s point of connection and vice versa.

This self-regulation effect helps not only in stabilising the voltage at distribution level, but it also balances fluctuating power flows that originate from non-dispatchable feedings (e.g. PV). When the sun is shining and the distribution grid's voltage goes up, this is a signal for voltage-sensitive loads to increase power consumption and vice versa.

It is also part of the power system stabilising scheme in large interconnections to dampen inter-area oscillations. By periodically modifying the reactive power of large generators, the transmission voltage is slightly varied, and these variations are also seen at distribution level. Consequently, dispersed resistive loads change their consumption pattern via this simple remote-control mechanism.

The emulation of the self-regulating effect with a continuously controllable device (e.g. an air conditioning with variable speed compressor, an electric vehicle or a stationary battery storage in charging mode) results in a $P(f,U)$ function as a set value P_{set}, which is chosen directly by the user or an energy management system, plus a frequency and voltage dependent term $\Delta P(f,U)$. With switchable devices, which can change between ON and OFF according to an internal energy storage (e.g. a fridge or a hot domestic water boiler), the switching threshold moves according to the grid's system state.

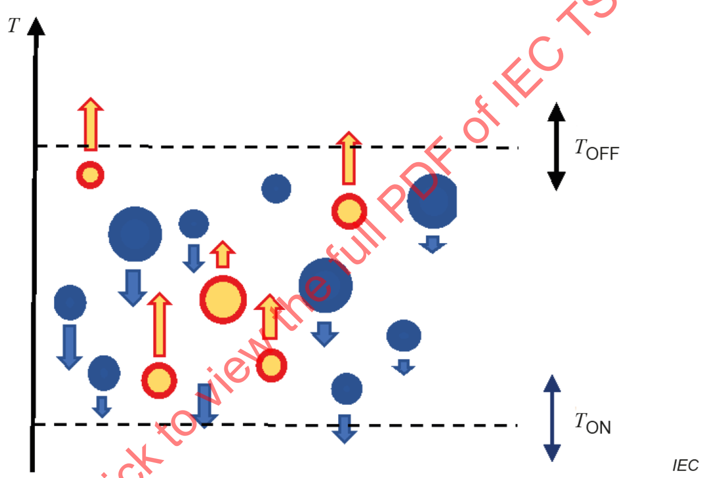


Figure A.2 – Particle model of switchable loads

Figure A.2 shows the particle model of switchable loads, for example electric water boilers which are functional electricity storages having a thermal energy storage after the conversion of electrical into thermal energy. The size of the circle indicates the thermal inertia, the length of the arrow gives the rate of change of temperature; dark particles are cooling down and light particles are heating up, changing direction at the T_{off} and T_{on} thresholds.

Large rapid movements of the frequency and voltage can result in large movements of the temperature threshold (T_{off} and T_{on}), which can switch a large portion of devices from on to off or vice versa. This can cause a synchronisation of the particles and can lead to a lack of particles which touch the threshold, until the different particle speed will desynchronise the particle swarm and fill the gaps around the threshold. Nevertheless, this method still delivers a first control response in case of major disturbance and provides a first line of defence. To avoid these negative effects after a major impact, one option is to choose k factors that are small enough, so that even with large changes of the input values (voltage, frequency), not the whole control reserve is used up. Another option is a further enhanced version of the control scheme which uses a randomised offset when determining that the particles hit the threshold, similar to a fuzzy set.

Annex B
(informative)

Choice of coefficients k_f and k_U

B.1 General

The choice of the coefficients k_f and k_U in Formula (3) and Formula (12) will depend primarily on the characteristics of the electrical system into which the item of equipment is connected. It can also depend on the type of equipment and its relative importance to the end-user of remaining in operation at undiminished output.

A small, isolated microgrid would be expected to experience frequency excursions that were much wider and occurred more often than those in a large interconnected electricity network. The frequency within a large interconnected electricity network would typically be very stable and readily controlled by the system operator through classical methods. Support from self-regulating loads would generally only be advantageous during major system disturbances. In contrast, a small, isolated microgrid would benefit more broadly from another method of matching generation to load and hence controlling frequency.

The downside of having the self-regulation of loads active continuously is that the equipment can operate for long periods of time below or above its set point power P_{set} if the frequency remains for long periods below or above the nominal frequency f_{set}. This could mean that the functioning of the equipment could be compromised from the end-user perspective. If the equipment were operating at less than rated power, this could be overcome to some extent by the equipment adjusting its set point power P_{set} to compensate for the discrepancy. For example, an air conditioner with load self-regulation capability in a 50 Hz microgrid would run at less than its set point power for as long as the frequency remained below 50 Hz. This would mean that the room temperature would gradually rise over time. If this continued for a sufficiently long period then the room temperature would increase sufficiently for the air conditioner to increase its set point power, say from 75 % to 100 % of rated power. This would have the effect of eventually counter-acting the self-regulation function and restoring the room temperature to the desired value. This, of course, would only be the case if the air conditioner were not already operating at 100 % of rated power.

B.2 Expression of coefficient k_f for self-regulation of frequency

The coefficient k_f is the gradient of the change in load power with change in frequency and has units of seconds (Hz^{-1}). It is also common to express this in terms of a droop setting. In this application, the droop is the percentage change in frequency required to produce a 100 % change in the load power. Thus a droop setting of 4 % means that a change in frequency of 4 % (2 Hz for a system frequency of 50 Hz and 2,4 Hz for 60 Hz) produces a 100 % change in the load power. Table B.1 gives various values of k_f and the associated droop values for 50 Hz and for 60 Hz systems.

Table B.1 – Relationship between k_f and droop for self-regulation of frequency

K_f Hz^{-1}	Δf for 100 % ΔP Hz	Droop	
		50 Hz system %	**60 Hz system** %
1,5	0,67	1,33	1,11
1,25	0,8	1,60	1,33
1,0	1	2,00	1,67
0,5	2	4,00	3,33
0,417	2,4	4,80	4,00
0,25	4	8,00	6,67
0,1	10	20,00	16,67

B.3 Example of frequency settings in an isolated microgrid

In this example an isolated microgrid has a nominal frequency of 50 Hz. The allowable maximum frequency range for this microgrid is 45 Hz to 55 Hz. If the frequency deviates outside this range, then the generators shut down and the system collapses. To aid the frequency stability of the microgrid, a number of loads within the microgrid are equipped to have a self-regulation function for frequency in accordance with Formula (B.1) to Formula (B.3). To provide maximum support for frequency stability, the equipment is not configured with a dead band and hence the self-regulation is always active. The self-regulating loads are to be configured such that there is no regulation at the nominal frequency of 50 Hz ($P = P_{set}$) but that the load power will reduce to zero for a change in frequency of 4 Hz from 50 Hz to 46 Hz.

The value of the parameter k_f can be calculated from the above information that a change in frequency from 50 Hz to 46 Hz, that is Δf = −4 Hz, should result in a reduction in load from $P = P_{set}$ to P = 0. Using these figures in Formula (B.2) gives a value of k_f of 0,25 Hz^{-1}. This corresponds to a droop of 8 %.

For events which give rise to a system frequency greater than 50 Hz, this will mean that load power doubles for a change in frequency from 50 Hz to 54 Hz. It should be noted that the load power of the equipment cannot be increased beyond its rated power, so that depending on the value of P_{set} at the time of the disturbance, there can only be limited capacity to increase the power drawn by the item of equipment.

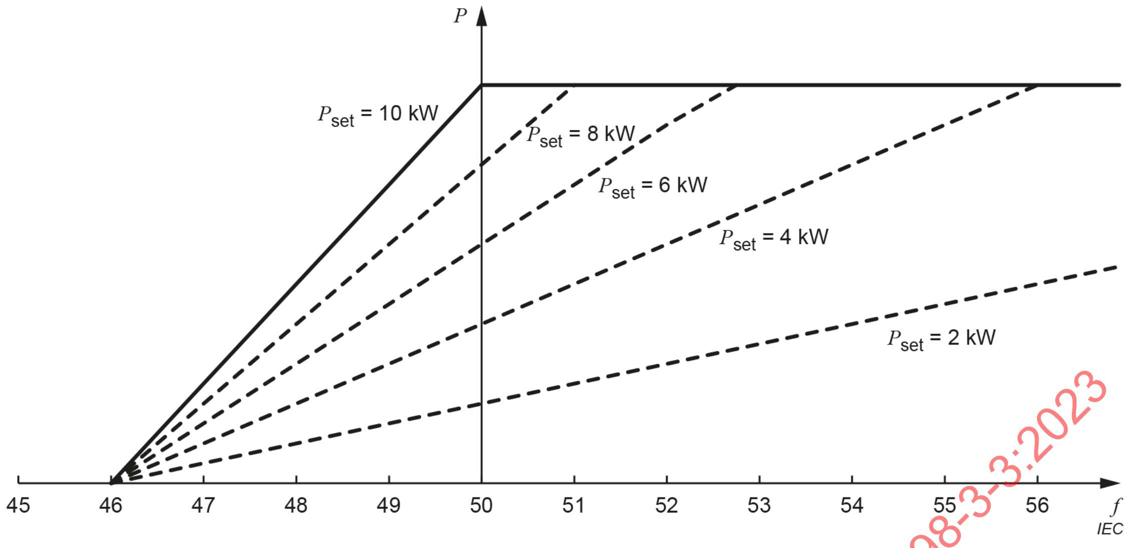
The self-regulation behaviour of the load in this example can thus be described by the following set of formulae.

$$P(f) = 0 \qquad \text{for } f \leq 46 \text{ Hz} \qquad \text{(B.1)}$$

$$P(f) = P_{set}\left[1 + 0{,}25 \cdot (f - 50)\right] \qquad \text{for } 46 \leq f \leq 50 \text{ Hz} \qquad \text{(B.2)}$$

$$P(f) = \min\left\{P_{set} \cdot \left[1 + 0{,}25 \cdot (f - 50)\right], P_{rated}\right\} \qquad \text{for } f \geq 50 \text{ Hz} \qquad \text{(B.3)}$$

Figure B.1 shows a graph of the above formulae for an item of equipment with a rated power of 10 kW and for power set points (P_{set}) of 2 kW, 4 kW, 6 kW, 8 kW and 10 kW. It should be noted that whilst the frequency range shown on the graph extends past 55 Hz, such high values of frequency are very unlikely to occur in practice.



Key

f frequency, expressed in hertz

P load power of the item of equipment, expressed in kilowatts

Figure B.1 – Example of *P*(*f*) self-regulation in an isolated microgrid

B.4 Example of frequency settings in a large interconnected network

In this example, the equipment is supplied from a large interconnected electricity network and the primary purpose of using equipment (loads) with self-regulation functionality is to reduce the load power in the event of an underfrequency event, so as to militate against the use of forced underfrequency load shedding. In the system considered, the rated frequency is 50 Hz and underfrequency load shedding is activated when the frequency drops to 49 Hz and continues in stages until all the available load is shed when the frequency has dropped to 47,5 Hz.

The normal frequency range of the system is 49,8 Hz to 50,2 Hz. Inside this range it is considered that there is no need for frequency response from self-regulation of loads and hence a dead band is selected corresponding to these two frequencies. This means that whilst the system frequency stays within the range 49,8 Hz to 50,2 Hz, the load power of the equipment is determined only by the set point of the load (temperature, etc.) and the power set point is not "over-ridden" to assist with power system stability.

Once the frequency drops below 49,8 Hz, the load power of the equipment is reduced in accordance with Formula (B.5). The aim of using self-regulation of load is to help stabilise the frequency and arrest its fall at a value above 49 Hz and thus avoid the need for forced load shedding. Thus the load power of self-regulating dispatchable loads should be reduced to zero by the time the frequency has dropped to 49 Hz.

The value of the parameter k_f can be calculated from the above information that a change in frequency from 49,8 Hz to 49 Hz, that is $\Delta f = -0,8$ Hz, should result in a reduction in load from $P = P_{set}$ to $P = 0$. Using these figures in Formula (B.5) gives a value of k_f of 1,25 Hz^{-1}. This corresponds to a droop of 1,6 %.

For events which give rise to a system frequency greater than 50,2 Hz, the same value of k_f is chosen for convenience. It should be noted that the load power of the equipment cannot be increased beyond its rated power, so that depending on the value of P_{set} at the time of the disturbance, there can only be limited capacity to increase the power drawn by the item of equipment.

The self-regulation behaviour of the load in this example can thus be described by the following set of Formula (B.4) to Formula (B.7).

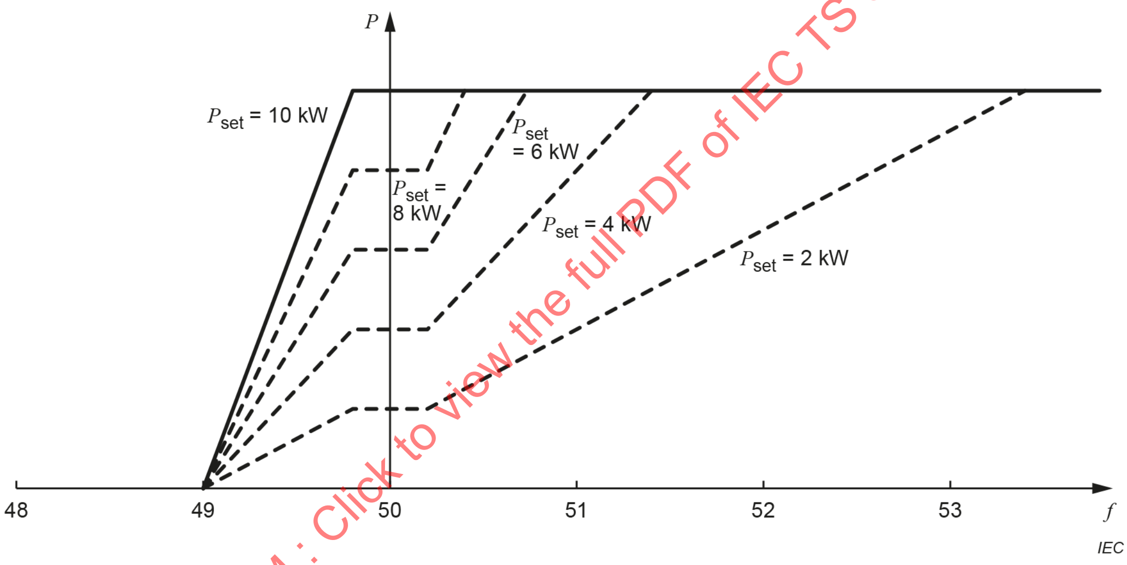
$$P(f) = 0 \quad \text{for } f \leq 49{,}0 \text{ Hz} \tag{B.4}$$

$$P(f) = P_{set} \cdot [1+1{,}25 \cdot (f - 49{,}8)] \quad \text{for } 49{,}0 \leq f \leq 49{,}8 \text{ Hz} \tag{B.5}$$

$$P(f) = P_{set} \quad \text{for } 49{,}8 \leq f \leq 50{,}2 \text{ Hz} \tag{B.6}$$

$$P(f) = \min\{P_{set} \cdot [1+1{,}25 \cdot (f - 50{,}2)],\ P_{rated}\} \quad \text{for } f \geq 50{,}2 \text{ Hz} \tag{B.7}$$

Figure B.2 shows a graph of the above formulae for an item of equipment with a rated power of 10 kW and for power set points (P_{set}) of 2 kW, 4 kW, 6 kW, 8 kW and 10 kW. It should be noted that whilst the frequency range shown on the graph extends past 53 Hz, such high values of frequency are very unlikely to occur in practice.



Key

f frequency, expressed in hertz

P load power of the item of equipment, expressed in kilowatts

Figure B.2 – Example of $P(f)$ self-regulation in a large interconnected network

B.5 Expression of coefficient k_U for self-regulation of voltage

The coefficient k_U is the gradient of the change in load power with change in voltage and has as unit the volt to the power minus one (V^{-1}). It is also possible to express this in terms of a droop setting. In this application, the droop is the percentage change in voltage required to produce a 100 % change in the load power. Thus a droop setting of 10 % means that a change in voltage of 10 % (23 V for a system with a nominal voltage of 230 V) produces a 100 % change in the load power. However, it should be noted that for a given nominal voltage, the droop value will change if dead bands are utilised. As such, the use of droop values for self-regulation of voltage is not as useful as for self-regulation of frequency, as voltage dead bands are likely to be required in almost all instances and will be much wider than any dead bands used in self-regulation of frequency. Table B.2 gives various values of k_U and the associated droop values.

Table B.2 – Relationship between k_U and droop for self-regulation of voltage

k_U	ΔU for 100 % ΔP V	Droop							
		110 V %	120 V %	130 V %	210 V %	220 V %	230 V %	240 V %	250 V %
0,200 V^{-1}	5	4,55	4,17	3,85	2,38	2,27	2,17	2,08	2,00
0,100 V^{-1}	10	9,09	8,33	7,69	4,76	4,55	4,35	4,17	4,00
0,050 V^{-1}	20	18,18	16,67	15,38	9,52	9,09	8,70	8,33	8,00
0,033 V^{-1}	30	27,27	25,00	23,08	14,29	13,64	13,04	12,50	12,00
0,025 V^{-1}	40	36,36	33,33	30,77	19,05	18,18	17,39	16,67	16,00

B.6 Example of voltage settings in an isolated microgrid

In this example an isolated microgrid has a nominal voltage of 230 V. The allowable sustained voltage range for this microgrid is from 207 V to 253 V. To aid voltage regulation within the microgrid, a number of loads within the microgrid are equipped to have a self-regulation function for voltage in accordance with Formula (B.7) and Formula (B.10).

Unlike frequency, voltages at different locations within the microgrid will be different, due to the voltage drop along conductors and the voltage rise caused by generators. While the voltage at a particular location could vary considerably, it is likely that some locations will experience voltages which are, over time, predominantly lower than the nominal voltage of 230 V and this lower voltage could continue for considerable lengths of time or even indefinitely. Conversely, some locations, particularly those close to generators will experience long periods during which the voltage is higher than the nominal value. These variations are normal and to be expected in any electricity network. Using self-regulation of loads for voltage control without a dead band would thus mean that some, and perhaps most, equipment would operate for long periods at a power either below or above its set point power P_{set}. This could well be unacceptable from the end-user perspective. Given that electrical equipment is designed to operate satisfactorily over a range of voltages, it would also be unnecessary from a system perspective. Thus, if self-regulation of loads for voltage control is enabled, it would be expected that a fairly wide dead band would be configured and that the self-regulation would only be expected to operate in the event of a contingency.

The calculation of the width of the dead band should be part of the design of the microgrid and take into account the possible voltage variations throughout the microgrid. In this example it is taken that the voltage at any point within the microgrid will fall within the range of 210 V to 250 V under normal operating conditions and this is thus used as the dead band. For satisfactory operation of equipment, it is considered that the voltage at any point in the microgrid should be 198 V or greater. To achieve this, the self-regulating loads for voltage control are to be configured such that the load power will reduce to zero for a change in voltage of 10 V from 210 V to 200 V.

The value of the parameter k_U can be calculated form the above information that a change in voltage from 210 V to 200 V, that is ΔU = -10 V, should result in a reduction in load from $P = P_{set}$ to P = 0. Using these figures in Formula (B.8) gives a value of k_U of 0,1 V^{-1}. This corresponds to a droop of 4,76 % at a voltage of 210 V.

For events which give rise to a voltage greater than 250 V, the same value of k_U is chosen for convenience. It should be noted that the load power of the equipment cannot be increased beyond its rated power, so that depending on the value of P_{set} at the time of the disturbance, there can only be limited capacity to increase the power drawn by the item of equipment.

The self-regulation behaviour of the load in this example can thus be described by the following set of equations.

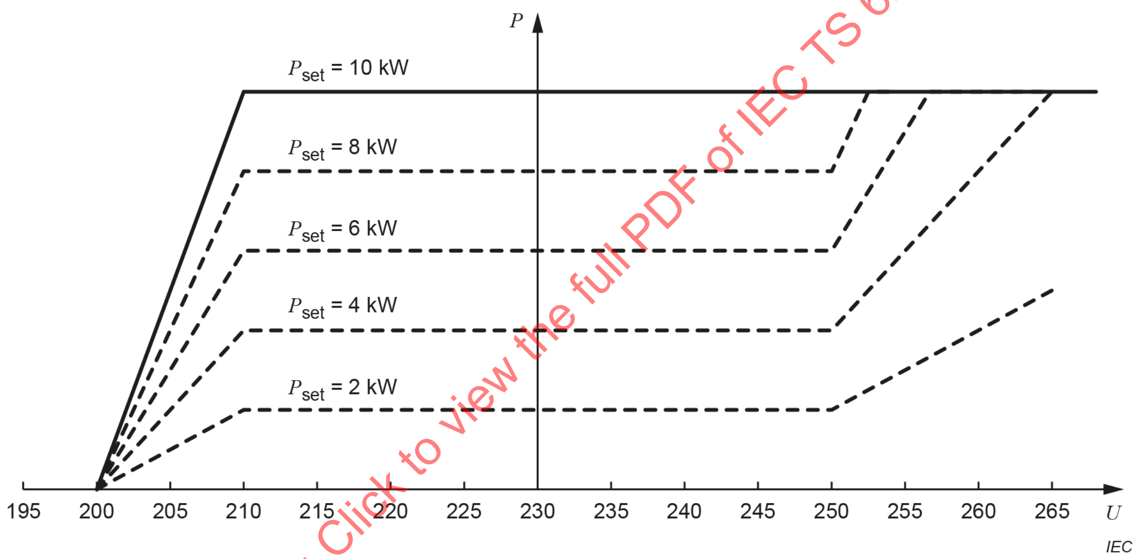
$$P(U) = 0 \quad \text{for } U \leq 200 \text{ V} \tag{B.8}$$

$$P(U) = P_{set} \cdot [1 + 0,1 \cdot (U - 210)] \quad \text{for } 200 \text{ V} \leq U \leq 210 \text{ V} \tag{B.9}$$

$$P(U) = P_{set} \quad \text{for } 210 \text{ V} \leq U \leq 250 \text{ V} \tag{B.10}$$

$$P(U) = \min\{P_{set} \cdot [1 + 0,1 \cdot (U - 250)], P_{rated}\} \quad \text{for } U \geq 250 \text{ V} \tag{B.11}$$

Figure B.3 shows a graph of the above formulae for an item of equipment with a rated power of 10 kW and for power set points (P_{set}) of 2 kW, 4 kW, 6 kW, 8 kW and 10 kW.



Key

U voltage, expressed in volts

P load power of the item of equipment, expressed in kilowatts

Figure B.3 – Example of $P(U)$ self-regulation in an isolated microgrid

Annex C
(informative)

Prioritization of loads

Different loads in microgrids can be assigned different priorities, according to the utility they provide and the size of their internal energy storage, resulting in shorter or longer storage time constants $\tau = E/P$. On the one hand, devices with shorter time constants should not be curtailed for a longer time period during an under frequency or under voltage situation. On the other hand, devices that deliver a higher utility should be curtailed less frequently. The prioritization is usually done on an individual case-by-case assessment. For example, an electric boiler providing hot domestic water (HDW) can have a higher utility than an auxiliary electric heater that supports the main heating system running on heating fuels. The decision if an electric charger of an electric bike has a higher priority than the HDW boiler will depend on the personal preference of how often to ride a bike and how to evaluate mobility needs compared to hot water supply.

Switchable loads shift their ON/OFF thresholds according to state-of-energy content of their internal energy storage, which means that devices with low energy are automatically prioritised and those with an almost full storage are at the end of the self-dispatching order. Even with an almost full energy storage, the load might be able to contribute a transient response contribution.

The prioritization can be done by shifting the $P(f)$ and $P(U)$ curves, and choosing a k_3 factor for the emulation of inertia that determines a low or high response to fluctuations of the input value. In the following, Table C.1 describes an example for setting the $P(f)$ function in a microgrid which is part of a larger 50 Hz interconnection. To be in line with the usual droop within that exemplary synchronous zone (assuming σ = 5 %) all 4 settings for priorities A-D share the same gradient of 40 %/Hz, in order to avoid transients in the interconnection while operating in the grid-connected mode.

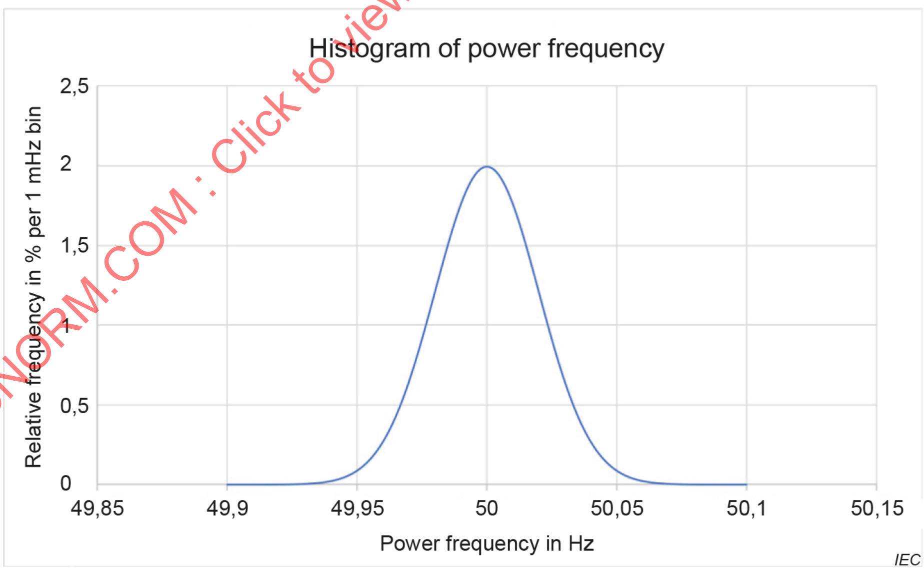


Figure C.1 – Frequency distribution of the power frequency of a 50 Hz network

Figure C.1 shows an ideal normal distribution (μ = 50 Hz, σ = 20 mHz) of power frequency measurements. The larger the share of dispatchable loads participating in dynamic self-regulating, the narrower will be the cone of the probability function. In island mode, it is assumed that the distribution widens up as shown in Figure C.2. The droop curves of the different priority types run in parallel. They bend down from the 100 % P_{set} line to a 40 %/Hz gradient at different break points f_{set}.

Table C.1 – Frequency domain (example for 50 Hz systems)

Priority level	$k_{1c,f}$ % P_{set} / Hz	f_{set} Hz
Type A	40	49,800
Type B	40	49,950
Type C	40	50,050
Type D	40	50,200

Table C.2 – Frequency domain (example for 60 Hz systems)

Priority level	$k_{1c,f}$ % P_{set} / Hz	f_{set} Hz
Type A	33	59,800
Type B	33	59,950
Type C	33	60,050
Type D	33	60,200

In these examples in Table C.1 and Table C.2, four different types have been chosen to allow different priorities. Type A has the highest priority, and will reduce power only at frequencies below 49,8 Hz (or 59,8 Hz) meaning that only rare frequency dips will trigger its self-regulating behaviour. Type B will react only if the frequency falls below 49,95 Hz (or 59,95 Hz), Type C will be engaged below 50,05 Hz (or 60,05 Hz) during most of the time, and Type D is practically always supporting the frequency – above 50,2 Hz (or 60,2 Hz) usually generators begin to reduce power according to their droop curve.

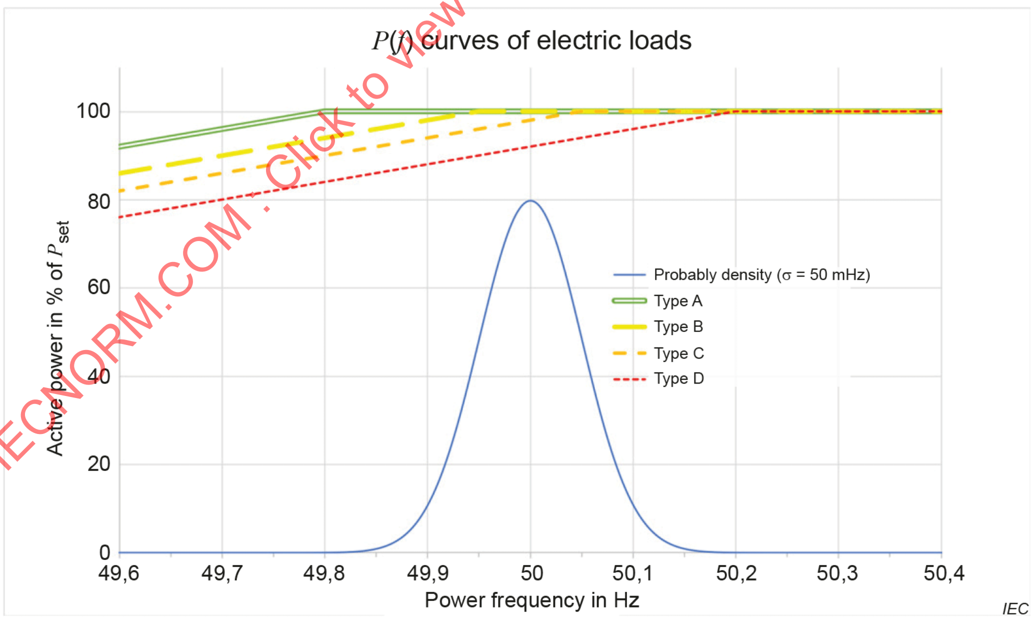


Figure C.2 – Four different droop curves according to prioritization

The approach for the voltage domain is similar. As voltage is a local characteristic of electric networks and depends on the distance to the next substation, on the temporal load profile as well as the structure of dispersed generation, no one-size-fits-all approach is applicable as in the domain of frequency which is a global signal. Instead, an adaptive control function is necessary which determines the mean μ and standard deviation σ at a given location and timeframe. During the change of seasons, the voltage pattern in areas with a high density of PV systems changes significantly, see Figure C.3.