IEC TS 62933-3-2

Edition 1.0 2023-01

TECHNICAL SPECIFICATION

colour inside

**Electrical energy storage (EES) systems –
Part 3-2: Planning and performance assessment of electrical energy storage systems – Additional requirements for power intensive and renewable energy sources integration related applications**

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ELECTRICAL ENERGY STORAGE (EES) SYSTEMS –

Part 3-2: Planning and performance assessment of electrical energy storage systems – Additional requirements for power intensive and renewable energy sources integration related applications

FOREWORD

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IEC TS 62933-3-2 has been prepared by IEC technical committee 120: Electrical Energy Storage (EES) Systems. It is a Technical Specification.

This Technical Specification is based on IEC TS 62933-3-1:2018 and is to be used in conjunction with IEC TS 62933-3-3:2022.

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

Draft	Report on voting
120/263A/DTS	120/278/RVDTS
	120/278A/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/publications.

A list of all parts in the IEC 62933 series, published under the general title *Electrical energy storage (EES) systems*, 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- withdrawn,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

This part of IEC 62933 should be used as a reference when planning, designing, controlling and operating power intensive and renewable energy sources integration related applications of EES systems.

ELECTRICAL ENERGY STORAGE (EES) SYSTEMS –

Part 3-2: Planning and performance assessment of electrical energy storage systems – Additional requirements for power intensive and renewable energy sources integration related applications

1 Scope

This part of IEC 62933 provides the requirements for power intensive and renewable energy sources integration related applications of EES systems, including grid integration, performance indicators, sizing and planning, operation and control, monitoring and maintenance. The power intensive applications of EES systems are usually used to improve the dynamic performance of the grid by discharging or charging based on corresponding control strategies. The renewable energy sources integration related applications of EES systems are usually used to mitigate short-term fluctuation and/or to keep long-term stability. This document includes the following applications of EES systems:

– frequency regulation/support;

– grid voltage support ($Q(U)$) ("volt/var support");

– voltage sag mitigation;

– renewable energy sources integration related applications;

– power oscillation damping (POD).

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 60721-1, *Classification of environmental conditions – Part 1: Environmental parameters and their severities*

IEC 61850 (all parts), *Communication networks and systems for power utility automation*

IEC TS 62786, *Distributed energy resources connection with the grid*

IEC TS 62933-1:2018, *Electrical energy storage (EES) systems – Part 1: Vocabulary*

IEC TS 62933-3-1, *Electrical energy storage (EES) systems – Part 3-1: Planning and performance assessment of electrical energy storage systems – General specification*

IEC TS 62933-3-3, *Electrical energy storage (EES) systems – Part 3-3: Planning and performance assessment of electrical energy storage systems – Additional requirements for energy intensive and backup power applications*

IEC TS 62933-5-1, *Electrical energy storage (EES) systems – Part 5-1: Safety considerations for grid-integrated EES systems – General specification*

IEC TS 62933-5-2, *Electrical energy storage (EES) systems – Part 5-2: Safety requirements for grid-integrated EES systems – Electrochemical-based systems*

IEC/IEEE 60255-118-1, *Measuring relays and protection equipment – Part 118-1: Synchrophasor for power systems – Measurements*

ISO 5660-1, *Reaction-to-fire tests – Heat release, smoke production and mass loss rate – Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)*

IEEE C37.118-2015, *IEEE Standard for Synchrophasors for Power Systems*

3   Terms, definitions, abbreviated terms and symbols

3.1   Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62933-1 and the following apply.

ISO and IEC maintain terminological 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

3.1.1
fast frequency response
fast frequency control
short duration application of an EES system used to slow down the frequency change rate of the electric power system (IEV 601-01-01) during sudden failures and reduce the amplitude of the transient frequency difference, through the capability to actively support grid frequency by discharging or charging very fast (e.g. within 100 ms)

3.1.2
fluctuation reduction
power smoothing
short duration application of an EES system used to reduce power oscillation fluctuation of power generation units (especially renewable energy sources) with regard to their point of connections (IEV 617-04-01) absorbing active power at times of high generation output and by feeding in additional active power at times of low generation output

3.1.3
power oscillation damping
POD
short duration application of an EES system used to restrain power oscillations in one or more connected AC electric power networks (IEV 601-01-02) by active or reactive power flow control

Note 1 to entry: Low frequency power oscillation range is typically from 0,1 Hz to 2 Hz.

3.1.4
primary frequency control
primary frequency regulation
short duration application of an EES system used to stabilize the electric power system (IEV 601-01-01) frequency on a steady state value through the capability to respond to a measured frequency deviation

Note 1 to entry: Generally, the primary frequency control is automatically activated by the primary control system within a few seconds from the measured frequency deviation and fully activated within less than a few minutes.

3.1.5
renewable energy resources generation firming
long duration application of an EES system used to decouple renewable energy source generation and energy consumption for a specific time by absorbing energy in periods with a surplus of energy generation and by provision of energy in periods with a surplus of energy consumption

3.1.6
secondary frequency control
secondary frequency regulation
short duration application of an EES system used to restore system frequency to the nominal system frequency usually following a primary frequency regulation

Note 1 to entry: Generally, the secondary frequency control is manually or automatically activated between 30 s up to 15 min from the primary frequency regulation completion.

3.1.7
self-discharge rate
percentage of the energy loss to full energy capacity of an EES system in the idle period during a predefined measurement time

Note 1 to entry: In the idle period all required peripherals are activated and their energy consumption is therefore counted.

Note 2 to entry: The measurement time is determined rationally according to the self-discharge characteristic of each EES technology.

3.1.8
voltage sag mitigation
voltage dip mitigation
short duration application of an EES system used to compensate the voltage drop during a specified time and for a predefined maximum power, when a voltage sag occurred at the primary POC

Note 1 to entry: The power quality events are described in IEC TS 62749. Voltage dip and voltage sag are frequently used as synonyms.

3.2   Abbreviated terms and symbols

3.2.1   Abbreviated terms

ACE   area control error

AGC   automatic generation control

BAMU   battery array management unit

BCU   battery control unit

BESS   battery energy storage system

BMS   battery management system

BMU   battery management unit

CAES   compressed air energy storage

DER   distributed energy resources

EES   electrical energy storage

EESS   electrical energy storage system

EMC   electromagnetic compatibility

EMS   energy management system

EV   electric vehicle

FAT   factory acceptance test

FES   flywheel energy storage

FFC	flat frequency control
FFR	fast frequency response
FTC	flat tie-line control
HMI	human machine interface
HVAC	heating, ventilation and air conditioning
HVDC	high voltage direct current
LCC	line-commutated converter
MOI	moment of inertia
OFRT	over-frequency ride through
OVRT	over-voltage ride through
PCC	point of common coupling
PCS	power conversion subsystem/power conversion system
PFR	primary frequency response
PMU	phase measurement unit
POC	point of connection
POD	power oscillation damping
PV	photovoltaic
ROCOF	rate of change of frequency
RSDR	reduction in standard deviation of ramp rate
RSDP	reduction in standard deviation of power
SAT	site acceptance test
SCADA	supervisory control and data acquisition
SCR	short-circuit ratio
SFR	secondary frequency response
SMES	superconducting magnetic energy storage
SOC	state of charge
SOH	state of health
SSI	subsynchronous interaction
SSR	subsynchronous resonance
SVC	static var compensator
TBC	tie-line load frequency bias control
UFRT	under-frequency ride through
UVRT	under-voltage ride through

3.2.2 Symbols

P	active power
Q	reactive power
S	apparent power
f	frequency
U	voltage
I	current

4 General planning and performance assessment considerations for EES systems

4.1 Applications of EES systems

4.1.1 Functional purpose of the EES systems

4.1.1.1 General

For the planning of EES systems, it is important to understand the purpose for which the EES systems should be used. It is also conceivable that EES systems can operate on more than just one application. Therefore, the planned applications of the EES systems in the grid to which they are connected should be described.

EES system applications can be distinguished according to various criteria necessary for applications of EES systems:

- demands on energy content;

- demands on active power input and output;

- demands on the frequency of phase transitions during charging and discharging;

- demands on response time and ramp rate performance;

- demands on additional reactive power exchange with the power supply system;

- demands on stand-alone and black-start capabilities.

Besides pure active power and energy applications an EES system can provide a wide range of ancillary services. Subclauses 4.1.1.2 to 4.1.1.5 differentiate between power intensive applications as well as energy intensive and backup power applications.

4.1.1.2 Power intensive applications

EES systems for power intensive applications generally have demands for fast step response performances, for frequent charge and discharge phase transitions or for additional reactive power exchange with the electric power system. Several mature EES technologies, in particular superconducting magnetic energy storage (SMES), supercapacitor, flywheel energy storage (FES) and power type lithium battery, have high power densities but low energy densities, and can be used in these applications. These applications include:

- grid frequency support/regulation;

- grid voltage support;

- power quality support;

- reactive power flow control;

- power oscillation damping (POD).

4.1.1.3 Renewable energy sources integration related applications

By integrating EES systems, various load, energy, power quality and operational management measures can be implemented, which can be used advantageously in combination with renewable energy sources. These applications are:

- power smoothing;

- energy generation firming;

- applications for electric charging stations in combination with renewable energy sources;

- load management (load fluctuation reduction);

- operational management.

4.1.1.4   Energy intensive applications

The energy intensive applications can provide the required power over a long period of time. The islanded operation of the EES system provides the required power to the internal electric power grids without relying on an external power source. Energy intensive applications of EES systems are:

- energy fluctuation reduction;
- islanded grid operation.

4.1.1.5   Backup power applications

In case of external grid power outage, the backup power application can provide the required power to all loads, or the emergency loads only within the internal grid. The backup power application of EES systems is:

- backup power supply and emergency support.

4.1.2   Application related requirements

4.1.2.1   General

To achieve the required functionality, the selected hardware and software of the EES system shall meet certain main functional requirements. These main functional requirements (not necessarily directly related to EES systems) are described in 4.1.2.

Therefore, the selected equipment shall have these main functional characteristics (e.g. supply and consumption of electrical energy), to properly deliver the functionality for the application. Typical requirements are listed in 4.1.2.2 to 4.1.2.13. Annex A provides further information about metrics relevant to each EES system application.

4.1.2.2   Power requirements

To specify demands on power input and output the following power values can be used to define power related requirements for EES systems:

- rated active power P [W];
- rated reactive power Q [var];
- rated apparent power S [VA];
- input and output power ratings [W];
- (rated) short-duration input and output power [W];
- short-duration reactive power [var];
- power density [W/kg], [W/m^3];
- ramp rate [W/min].

4.1.2.3   Time requirements

Time values to express the duration of a certain power application can be used to specify energy and power performance requirements for EES systems:

- rated charging/discharging duration;
- rated short-duration input/output power time.

4.1.2.4 Energy requirements

To specify demands on energy consumption and supply at the POC the following energy values can be used to define energy related requirements for EES systems at the POC:

- rated energy capacity [kWh];

- actual energy capacity [kWh];

- energy density [kWh/kg, kWh/m^3].

The energy requirements should consider the capacity fading with time to fulfill its service life.

4.1.2.5 Efficiency requirements

To describe the efficiency of a power conversion or transport process as well as of an energy storage process the following energy and power related efficiency values can be used to specify efficiency requirements for EES systems:

- power efficiency [%];

- PCS efficiency [%];

- rated roundtrip energy efficiency [%];

- self-discharge rate [%/day].

4.1.2.6 Response time and ramp rate requirements

The speed requirements, that is, how fast the actual value is reached with sufficient accuracy when a setpoint value is given, can be defined by requirements regarding response time and ramp rates:

- step response time;

- ramp rate;

- settling time;

- frequency measurement time.

When switching between charging and discharging, the following values can be used:

– resting time;

– idle time;

– transition time.

4.1.2.7 Control requirements and characteristics

In order to obtain the desired functionality, suitable algorithms and characteristics shall be implemented in the control of the EES system:

- frequency regulation capability with a frequency-active power characteristic ($P(f)$);

- voltage support capability with a voltage-reactive power characteristic ($Q(U)$);

- voltage sag mitigation;

- renewable energy sources (power) smoothing;

- renewable energy sources (energy) firming;

- EES systems in electric charging stations in combination with renewable sources;

- power oscillation damping;

- black-start capability.

NOTE   In some cases, voltage support to prevent voltage collapse after a transmission contingency $(N-1)$ requires both reactive and active power. The application related to voltage support of EES system mainly considers reactive power characteristics.

4.1.2.8   Requirements regarding size, weight and dimensions

There can also be requirements for EES systems concerning spatial dimensions and weight:

- dimensions (length, width, height) [m], footprint [m^2], volume [m^3];
- weight [kg, t].

4.1.2.9   Requirements and characteristics regarding security

There can also be requirements for EES systems concerning security:

- equipment security;
- cyber security;
- operational security;
- security protection measures;
- fire protection security;
- complying with the specific security standards for each scenario.

4.1.2.10   Requirements and characteristics regarding lifetime

There can also be requirements for EES systems in terms of lifetime:

- minimum number of cycles in total, per year or per day;
- minimum calendrical lifetime;
- ambient temperature and other climatic conditions.

4.1.2.11   Requirements and characteristics regarding environmental compatibility

There can also be requirements for EES systems concerning the environmental impact and compatibility:

- maximum CO_2 emissions during production, operation and disposal use;
- maximum noise emissions during production, operation and disposal;
- other substances released into air, water or soil (possibly dependent on the storage technology used within the EES system) during production, operation and disposal.

4.1.2.12   Requirements regarding availability and usage

If it is a safety relevant application, there can be requirements regarding availability and usage of the EES system:

- number of redundant systems;
- maximum downtime per year;
- minimum system utilization rate;
- preventive maintenance and corrective maintenance operations.

NOTE   Preventive maintenance is a kind of maintenance carried out with the intention to assess and/or to mitigate degradation and reduce the probability of failure of an item. Corrective maintenance is a kind of maintenance carried out after fault recognition and intended to restore an item into a state in which it can perform a required function.

4.1.2.13   Requirements and characteristics regarding economic efficiency

There can also be considerations for EES systems in terms of economic efficiency:

- maximum investment costs;
- maximum operational costs;
- maximum overheads.

During the planning phase this can have an influence on the selection of the technology used within the EES system (e.g. storage technology of the accumulation subsystem).

4.2   Conditions and requirements for connection to the grid

4.2.1   General

The requirements coming from the grid to which the EES system is to be connected are described in 4.2. These include requirements, conditions and limitations of the grid, and requirements for the operator as well as legal and technical/functional regulations.

4.2.2   Grid parameters at the intended POC

Subclause 4.2.2 describes the electrical environment of the EES system, which shall be considered for design of an EES system. It contains grid parameters and requirements, which include mainly electrical parameters, constraints, operational ranges and requirements of the electrical power grid at the (primary) POC.

The main parameters of the grid at the POC, to which the EES system is going to be connected, shall be considered in the planning phase. These parameters include:

- nominal voltage of the service;
- operation voltage range for equipment;
- temporary voltage variations;
- nominal frequency;
- continuous normal frequency variation;
- temporary frequency variations;
- short-circuit current and duration;
- circuit breaker synchronization;
- neutral connection;
- protective earthing;
- indicative characteristics regarding the quality of the voltage waveform;
- protection requirements.

4.2.3   Service conditions

Subclause 4.2.3 considers requirements regarding service conditions, which include the non-electrical environment of the EES system:

- (ambient) temperature;
- humidity;
- lightning;
- earthquake;
- flooding/inundation, water, rain;
- pressure;

- wind;

- ice and snow;

- invasion of life forms (e.g. mice, insects or humans);

- vibration and resonant oscillations;

- dust and smoke;

- corrosive atmospheres;

- salt mist/salt water/erosive chemical;

- fire (internal and external);

- external electromagnetic sources;

- solar irradiation/solar radiation;

- sediment build up.

According to the place of installation the site-specific requirements shall be considered during the planning phase.

In addition, the classification of environmental conditions in IEC 60721-1 shall be considered. Where applicable, EES system planners should refer to IEC 60721-3-3, IEC 60364-5-51 or IEC TS 62933-4-1 for guidelines on environmental conditions.

4.2.4 Requirements and restrictions of the grid or system operator

4.2.4.1 General

In 4.2.4 the requirements and restrictions are listed, which come mainly from the grid structure and the operation of the EES system. These parameters are typically provided by the grid or system operator and can be included in specific grid requirements based on local grid codes.

The voltage level of the EES system shall meet the requirements of the application objects, and the voltage level shall be determined comprehensively in accordance with the performance, location and specific conditions of the EES system.

When selecting the POC to which the EES system is to be connected, the following aspects should be considered:

- requirements for grid security;

- problem of short-circuit capacity;

- load capacity;

- impact on power quality.

4.2.4.2 Power system profile at the POC

The power system profile at the POC is defined by the steady state and dynamic range of frequency and voltage conditions in which the EES system shall remain connected to the POC and provide the EES system capabilities and required functions. Moreover, admitted power electronics blockage, under certain voltage drops and over-voltages, and transient over-frequency capabilities should be stated (refer to IEC TS 62786), as well as application scenarios and local regulations where needed. The following items should be considered:

- duty cycles;

- load profiles;

- short-circuit current contribution;

- contribution to voltage/current harmonics;

- voltage ride through capability (UVRT/OVRT);

- frequency ride through capability (UFRT/OFRT);

- active power transfer during fault and recovery after fault clearance;

- externally or internally auxiliary power supplied;

- accuracy and tolerances of values/measurements;

- monitoring/data requirements;

- additional grid requirements (including hardware and software interfaces).

4.2.4.3   Permitted range for energy management

Since the initial value at the beginning of each duty cycle should be within a certain energy content range, a recovery cycle can be necessary to bring back the EES system to the initial or specific state where it is possible to perform duty cycles again. The degrees of freedom in recovery cycles depend mainly on grid requirements. Regarding sizing of the EES system, the following characteristic values of recovery process should be given:

- range of allowable active output or input power, including maximum and minimum active output or input power values;

- minimum and maximum duration;

- minimum and maximum recovery times, which are available to restore the EES system between duty cycles;

- possible requirements or constraints regarding reactive input and output power;

- allowable range of frequency values;

- maximum allowed ramp rates of active and reactive power;

- allowable range of power factor values at primary POC;

- possible requirements regarding power factor.

4.2.4.4   Duty cycles

The application of EES systems is usually connected to the identification of one or more suitable duty cycles, which the EES system can typically have to perform at the primary POC to meet its operational requirements.

The specification of the identified duty cycles should include:

- duration of the duty cycle and the expected frequency (number of times per day/week/year);

- required pattern of the active power at the primary POC of the EES system, possibly including allowed tolerance ranges (maximum overshoot and/or undercut);

- required pattern of the reactive power at the primary POC of the EES system, possibly including allowable tolerance ranges (maximum overshoot and/or undercut).

The pattern of active and reactive power at the primary POC can include durations in which the active and/or reactive power is zero. From these patterns it should be possible to derive ramp rates of the active and reactive power.

4.2.4.5   Lifetime

The required service lifetime of the EES system should be specified with regard to the proper consideration of system ageing and possibly necessary maintenance and refurbishment works.

In IEC TS 62933-1 the following terms regarding lifetime are defined, which can be used for requirements of the EES systems:

- service life;

- expected service life;

- end-of-service life.

4.2.4.6   Data requirements

For operational and planning purposes, the network operator or the operator of a higher-level control station usually requires certain operational and forecast data from the EES system, for example

- actual input/output energy capacity;
- actual input/output power capability;
- forecasts regarding power input and output including durations.

4.2.4.7   Safety

In IEC TS 62933-1 and IEC TS 62933-5-1 the following terms regarding safety are defined, which can be used for requirements of the EES systems:

- safe state;
- unsafe state;
- risk assessment;
- risk evaluation.

4.2.5   Standards and local regulations

4.2.5.1   General

The EES system connected to the grid shall comply with standards and can be subject to local regulations to ensure the safe and stable operation of the EES system and the grid. All standards which impact the EES system design shall be explored in the planning phase.

4.2.5.2   Grid connection standards

4.2.5.2.1   Grid codes

The most important technical requirements for grid connection that the EES system shall meet are described in the grid code. The grid codes define the principle governing the relationship with the EES system and the technical standards that the grid and the EES system shall meet.

4.2.5.2.2   Standard performance assessment criteria

For some applications, the EES system should demonstrate certain performance characteristics when connected to the grid, for example pre-qualification criteria, in order to obtain approval to participate in the primary control market.

4.2.5.2.3   Selection of voltage level and POC principles

The selection of voltage level and POC shall comply with the relevant technical regulations and meet the economic and safety requirements of the grid for the EES system.

The voltage level of the EES system shall meet the requirements of the application objects and shall be determined comprehensively in accordance with the power, application location and specific conditions of the EES system.

The selection of the POC should consider:

- the requirements for grid security;
- the problem of short-circuit capacity;
- the load capacity;

- the impact on power quality.

4.2.5.3   General standards and local regulations

The EES system connected to the grid can be subject to relevant national standards, industrial standards and enterprise standards With regard to the connection of EES systems, the following standards shall be complied with:

- technical regulations;
- automation and communication regulations;
- energy measurement regulations;
- relay protection and automatic safety devices regulations;
- environment related regulations.

4.3   Design of the EES systems

4.3.1   General

Subclause 4.3 deals with the design and the grid integration of EES systems and possible resulting requirements. In addition to requirements related to the components, 4.3 also contains specifications regarding operation, control, data exchange, monitoring and maintenance.

4.3.2   Structure of the EES systems

The design of the EES system includes the selection of the system architecture and the selection of the subsystems. The typical architecture of an EES system, which internally feeds the auxiliary subsystem, is shown in Figure 1a).

a)   EES system without auxiliary POC

b)   EES system with auxiliary POC
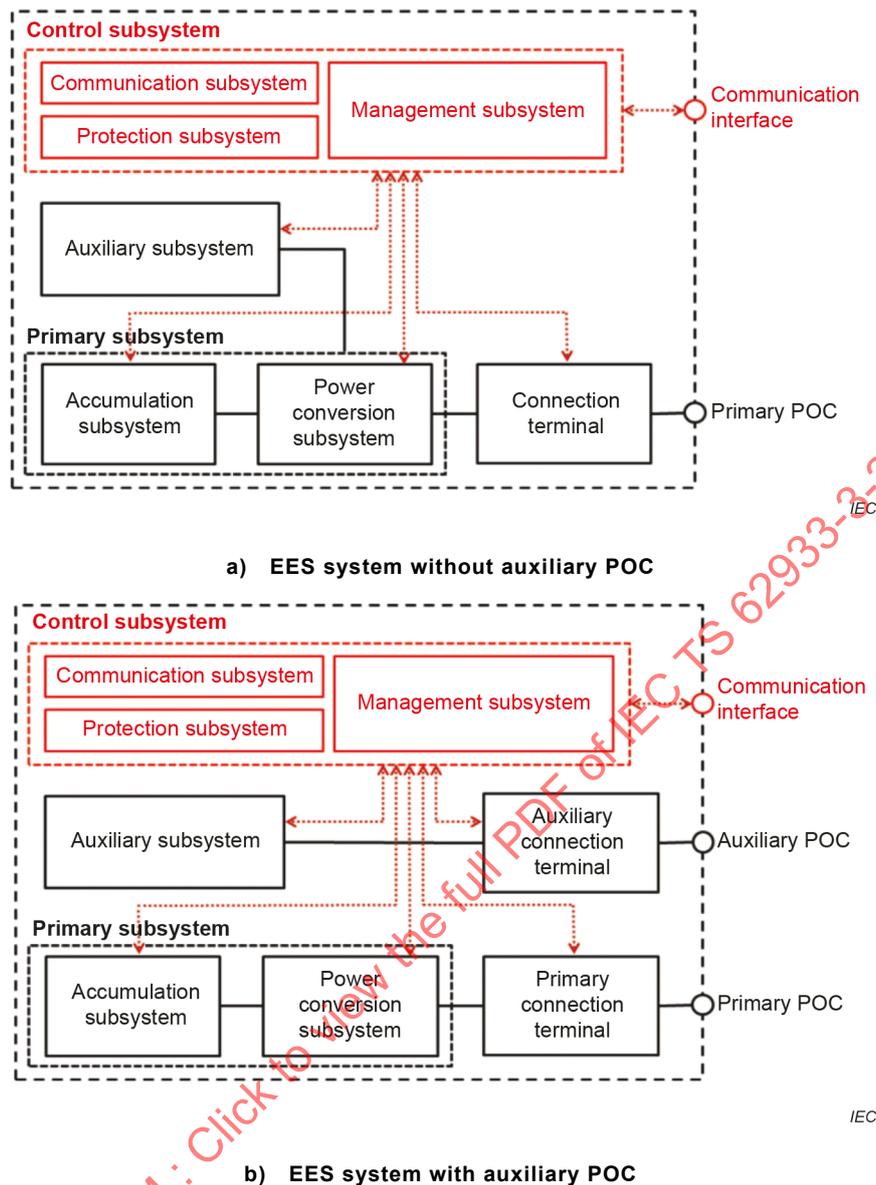
Figure 1 – Typical architectures of EES systems

If the auxiliary subsystem of an EES system is fed from another feeder, the architecture is shown in Figure 1b).

The requirements of the subsystems of an EES system are described in 4.3.3. In general, for all subsystems, the contribution to the overall system efficiency, for example roundtrip efficiency, shall be indicated.

4.3.3   Subsystem specifications

4.3.3.1   General

To meet the requirements of the entire system, it is necessary to break down the system requirements to the requirements of the subsystems. The requirements for the subsystems shall be formulated in a general and technology-independent manner. But requirements arising from the subsystems (e.g. regarding safety or maintenance), which are technology dependent, shall also be considered.

Constrains between power rating, available energy, ambient conditions and other internal/external aspects shall also be considered for all subsystems.

4.3.3.2   Accumulation subsystem

The energy capacity of the accumulation subsystem of the EES system has to be evaluated in an appropriate way with respect to the energy form. The energy capacity of the accumulation subsystem directly influences the rated input and output energy capacity at the primary POC, i.e., it influences the active input and output power values at the primary POC as well as the duration the active input and output power can be applied at the primary POC.

Accumulation subsystems shall meet performance specifications throughout their service life. This includes their service life under use conditions such as operation patterns (see IEC TS 62933-1:2018, Figure 1), environmental conditions, maintenance cycle, etc.

a) General requirements

The following information shall be provided irrespective of the technology applied:

For each accumulation subsystem the energy storage capacity and the maximum charge and discharge power shall be considered, because this has a direct influence on the overall EES system.

Also, the present energy content is important for the EES system. A forecast method, i.e. how the resulting energy content after charging or discharging with a certain power for a certain time can be estimated, shall be given.

Typical service life values (possibly differentiated into cyclical and calendrical ageing) shall be specified. Information on the energy and power density shall also be given to be able to make a comparison with other accumulation subsystems if necessary.

Information about necessary service and maintenance cycles shall be given. The auxiliary power demand of the accumulation subsystem shall also be provided, if applicable:

• efficiency parameters of the accumulation subsystem;

• charging efficiency of the accumulation subsystem;

• discharging efficiency of the accumulation subsystem;

• self-discharge or "energy storage efficiency" of the accumulation subsystem.

b) Specific requirements

If there are requirements that are specific to the accumulation technology applied, then these requirements shall be mentioned here. For example, if a reduction in charging or discharging power is necessary in certain operating areas, this shall be indicated. If special regulations have to be considered for the accumulation subsystem (for example, for disposal), this shall be specified here, as it could be relevant for planning. If galvanic isolation between the POC and accumulation subsystem is provided, it shall also be given here.

4.3.3.3   Power conversion subsystem

The power conversion subsystem converts the power of the accumulation subsystem into electrical power at the POC, typically AC output power during discharge of the accumulation subsystem, and can convert grid AC input power to suitable power for charging the accumulation subsystem. This conversion can be performed by electrical and/or mechanical systems. The power conversion subsystem influences the apparent power characteristic of the EES system. The power conversion subsystem can also influence the power quality at the POC.

Generally, the power conversion subsystem is connected to the accumulation subsystem and to the (primary) connection terminal. For planning issues, the power conversion subsystem shall also include all power transfer apparatus between the connection terminal and the accumulation subsystem, for example any kind of power transformer, sine filter or switching elements.

a) General requirements

The following information shall be provided irrespective of the technology applied:

The auxiliary power demand of the power conversion subsystem shall also be given here, if applicable. If galvanic isolation between the POC and accumulation subsystem is provided, it shall also be given here:

- efficiency parameters of the conversion subsystem;
- charging efficiency of the power conversion subsystem;
- discharging efficiency of the power conversion subsystem.

b) Specific requirements

If there are requirements that are specific to the power conversion technology applied, then these requirements shall be mentioned here. The conversion type (AC/DC, AC/AC, pump/generator, etc.) as well as the operational ranges, for example the DC voltage or frequency range, shall be given.

4.3.3.4 Auxiliary subsystem

All necessary equipment intended to perform the EES system's auxiliary functions shall be used, for example, HVAC (heating, ventilation, and air conditioning system) and fire suppression system.

a) General requirements

The following information shall be provided irrespective of the technology applied:

The overall auxiliary power demand of the EES system which has to be handled by the auxiliary subsystem shall also be given here. Auxiliary power demand for every noteworthy operational state of the EESS shall be provided, within the expected influence of the climate conditions such as outdoor air temperature and solar irradiation. Information regarding the structure of the auxiliary subsystem shall be provided.

Furthermore, requirements regarding redundancy and buffered power supply (in case of an outage of the supplying power source) shall be given, if applicable.

b) Specific requirements

If there are requirements that are specific to the auxiliary subsystem technology applied, then these requirements shall be mentioned here.

4.3.3.5 Control and management subsystem

A system for monitoring and controlling the EES system shall be used. A control subsystem can include a communication subsystem, protection subsystem and management subsystem. During the planning phase the required remote-control capabilities and the operation modes that the control system will support shall be stated, considering the applicable local grid code requirements.

The EES system shall be designed in such a way that a supply outage does not affect the EES system security and the ability of the EES system to start up again. The maximum outage duration shall be considered (for example a specific backup power has to be designed). A safe disconnection and safe system shutdown concept shall be agreed between supplier and user of the EES system.

All protection functions shall be described with functionality and trigger values.

a) General requirements

The typical architecture of the EES system shown in Figure 1 depicts the management subsystem as a single system. When an EES system is designed and installed, it is common to provide separate management systems for the accumulation subsystem and power conversion subsystem. In addition, the energy management system can be placed so as to control the internal operation of the EES systems and to interact with the grid power systems. Figure 2 depicts the detailed structure of the management subsystem including the management system for the accumulation subsystem, the management system for the power conversion subsystem, and the energy management system. Depending on the design, these systems can be provided as separate systems or as functions within a single system.
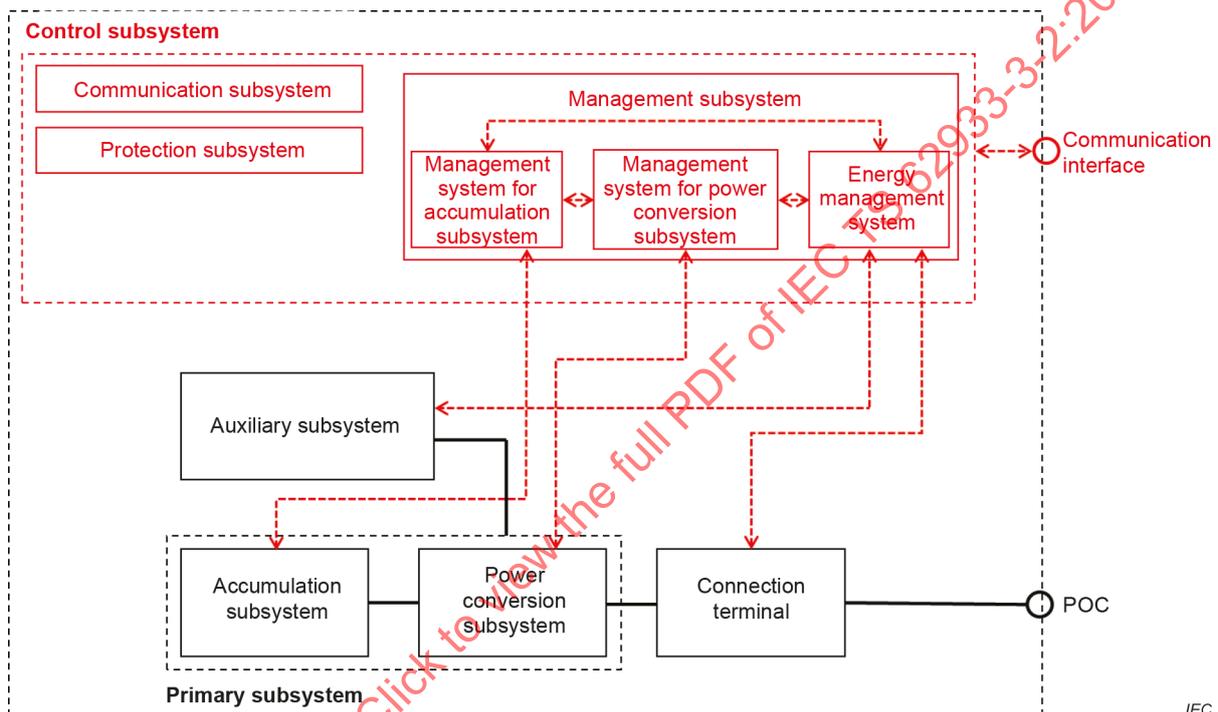
Figure 2 – EES system typical architecture with detailed structure of management subsystem

The management subsystem shall include the management system for the accumulation subsystem and the power conversion subsystem. The energy management system can be included in the management subsystem. The functional requirements for the management system for the accumulation subsystem, the power conversion subsystem and the energy management system are defined as follows:

- management subsystem for accumulation subsystem:
  - measurement function;
  - calculation function;
  - control function;
  - communication function;
  - protection function;

- management subsystem for power conversion subsystem:
  - measurement function;
  - control function;
  - protection function;
  - communication function;
  - recording function;
  - monitoring function;
- energy management subsystem:
  - control function: scheduling, EES system subsystems control;
  - communication function: communication with EES system subsystems and grid power systems;
  - calculation function: load change forecast, charge/discharge power, statistics;
  - monitoring function: input/output power, states of primary subsystems.

b) Specific requirements

If there are requirements that are specific to the control subsystem technology applied, then these requirements shall be mentioned here.

4.3.4 Grid integration of the EES systems

4.3.4.1 General considerations

The connection scheme and the structure of the overall system used to realize the application are provided in 4.3.4

The EES system shall be in compliance with the requirements of the grid operator.

The EES system connection to the grid shall be described, including the switchgear interface, the expected interrupting and isolating capabilities, the protection scheme coordination (protection functions, tripping times, etc.) and the instrument transformers placement for measurement.

To realize the effective operation and monitoring of the EES system from the grid point of view, the EES system should be operated in accordance with its rated characteristics and present capabilities through the information exchanged with local and/or remote power management systems. Grid operators can directly or indirectly manage the EES system.

If an EES system is used in an islanded environment, the interaction between the EES system and the external grid is not required. However, in this case, the EES system could interact with other distributed energy sources such as PV, wind turbine, etc. and coordinate their operation or accept their coordination.

4.3.4.2 Additional components and requirements

The structure and the requirements of additional system components, for example fast switch or bypass circuit, shall be provided.

4.3.5 Operation and control

4.3.5.1 General

The EES system shall be capable of exchanging information with the grid operator, and upon mutual agreement, shall be able to be monitored and controlled by the grid operator. To ensure the secure operation of the grid and EES system, the EES system shall meet the following requirements:

- The parameters and commands exchanged between the EES system and the grid operation systems shall be agreed.

- Depending on local system requirements, the EES system shall accept the control and regulation instructions sent by the grid operator.

IEC 61850 (all parts) shall be used, and other standards can be considered, to define requirements for operation and control of EES systems, for example for the data model of the EES system or for operation and control modes.

The control modes of the EES system shall be chosen in accordance with the specific requirements in different application scenarios.

In IEC TS 62933-1 the following terms regarding operation and control of EES systems are defined:

- operating state;
- stand-by state;
- stopped state;
- operation signals;
- shutdown;
- operating procedure;
- emergency stop;
- operating mode;
- intentional islanding;
- unintentional islanding;
- active power flow control;
- feeder current control;
- grid frequency control;
- nodal voltage control;
- power quality events mitigation;
- reactive power flow control;
- hybrid and emergency application;
- outage mitigation.

4.3.5.2 Operation states of the control subsystem

There are different kinds of operation states which can be adopted for the control of an EES system. If grid connected, the EES system can be operated with different kinds of active power controls, for example:

- grid frequency support;
- islanding control and black start capability;
- active power limitation;
- manual active power control;

- pattern active power control;

- automatic load following control;

- power control modes for grid voltage support;

- constant value control modes;

- voltage-related control modes;

- active power related control modes;

- voltage-related active power reduction.

4.3.6 Monitoring

4.3.6.1 General

During operation within the EES systems a lot of values (e.g. voltages, currents, temperatures) are measured and monitored. To allow the system operator to monitor important values of the EES system, there shall be a data interface for exchanging monitoring data. The important values shall include the following items:

- values for accumulation subsystem: voltage, current, temperature, key parameters or indicators related to technology (e.g. rotational velocity of flywheel, moment of inertia (MOI) of the rotor), etc.

- values for power conversion subsystem: active power, reactive power, frequency, voltage, current, operation mode, etc.

The monitoring interface of the EES system shall meet the following requirements:

– agreement on the values of the EES system to be monitored;

– providing the monitoring data requested by the grid operator depending on functional requirements.

Besides internal values the EES system shall monitor the electric values at the POC (e.g. voltage, current, active and reactive power exchange or available energy). Also, the status of equipment within the EES system shall be monitored (e.g. switching devices or tap changer positions of transformers). IEC 61850 (all parts) shall be used; other standards can be considered.

4.3.6.2 General requirements

The information shall be provided irrespective of the technology applied.

Data requirements for the monitoring of EES systems shall be given here.

4.3.6.3 Specific requirements

If there are requirements that are specific to the monitoring of the EES system applied, then these requirements shall be mentioned here, for example for accumulation subsystems or power conversion subsystems.

4.3.7 Maintenance

Information on maintenance cycles and downtime during the maintenance of the EES system shall be provided, for example periodical inspections of the accumulation subsystem or the power conversion subsystem.

Furthermore, the maintenance of EES systems and their subsystems is typically very technology dependent. These requirements shall be provided.

4.3.8 Communication interface

The requirements for the information exchange of the EES system with other systems are described here. The information exchange can include communication with the superior system, monitoring, controlling, measuring, and recording faults. The communication interfaces should be in accordance with data models and communication services conforming to standards in order to keep interoperability with the grid.

The EES system shall maintain time synchronization during the operation with its subsystems and the superior system. The EES system shall use standard-based communication protocols. The data information model shall consider the relevant standards. IEC 61850 (all parts) shall be used; other standards such as DNP3 can be considered.

4.4 Sizing and resulting parameters of the EES systems

4.4.1 General

Considering all the requirements of 4.1, 4.2 and 4.3, the EES systems can be dimensioned. The sizing and resulting parameters of the EES systems are described in 4.4.2.

4.4.2 Sizing

4.4.2.1 General

For sizing of the EES systems all the requirements and restrictions of 4.1 to 4.3 shall be considered. During the planning phase, possible performance degradation of the EES system over the lifetime shall also be considered. The necessary maintenance cycles and service conditions shall be taken into account as well.

The required duty cycles, the specified recovery times and the required service life can be used to derive the size of the EES system. For the sized EES system, the required duty cycles can be met, and the system can recover in specified time periods over the whole service life under a certain operation strategy.

All (superposed) duty cycles which are necessary to describe the overall operational capability of the EES system shall be considered, to identify the characteristic values of the duty cycles. The recovery cycles and their characteristic values should also be superposed.

4.4.2.2 Requirements for sizing and planning

When performing the sizing and planning process of the EES system, the following requirements shall be met:

- Power capabilities and energy storage capacity shall be met.

- Different control strategies shall be considered.

- Lifetime and ageing of components and subsystems, charge-discharge characteristics and charge-discharge cycles shall be considered.

- In general, all requirements in 4.1 to 4.3 shall be investigated and considered in the EES planning and design process.

4.4.2.3 Overview EES planning and design process

Figure 3 is the illustration of the main topics that shall be investigated in the EES planning and design aspects.
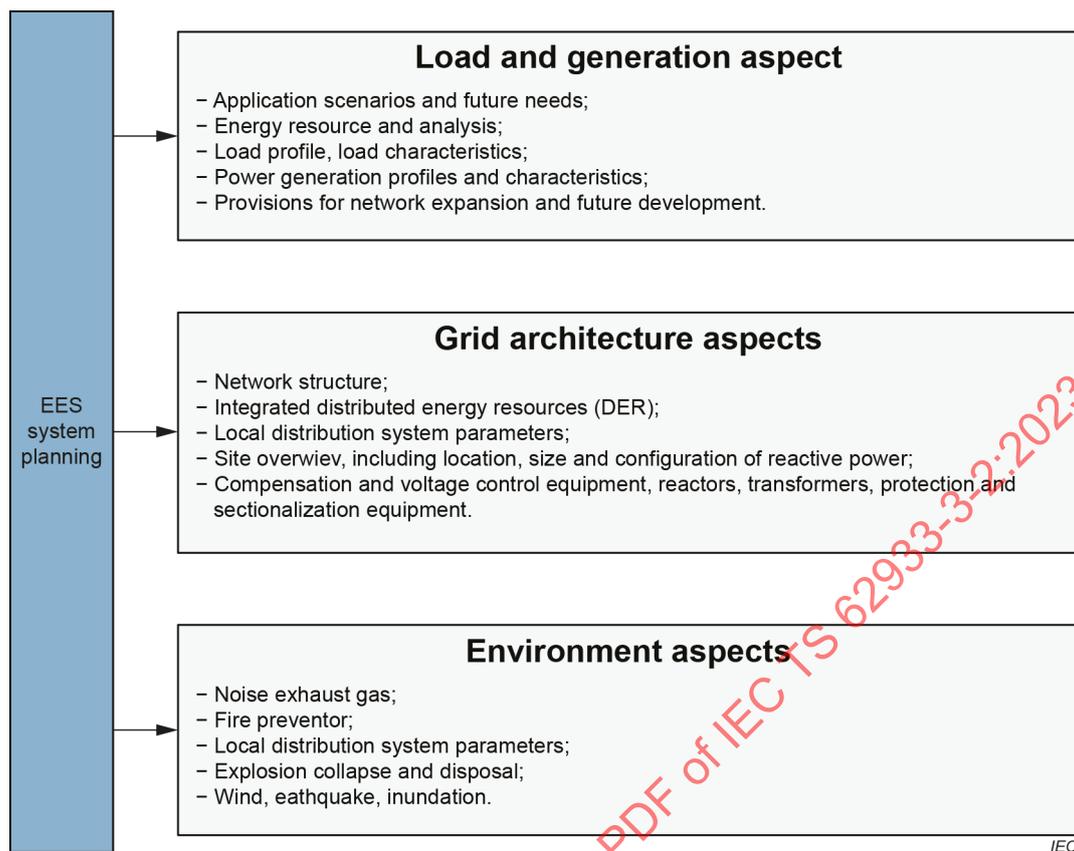
Figure 3 – Overview of EES planning and design aspects

In many cases, EES systems are planned with multi-function applications. Figure 4 gives an example of the EES planning process with multi-function applications. The main procedures include:

- identifying the functional objective: requirement of power dispatching and minimum of EES energy;

- considering constraints: EES energy balance, system power balance, SOC operation limit, etc.
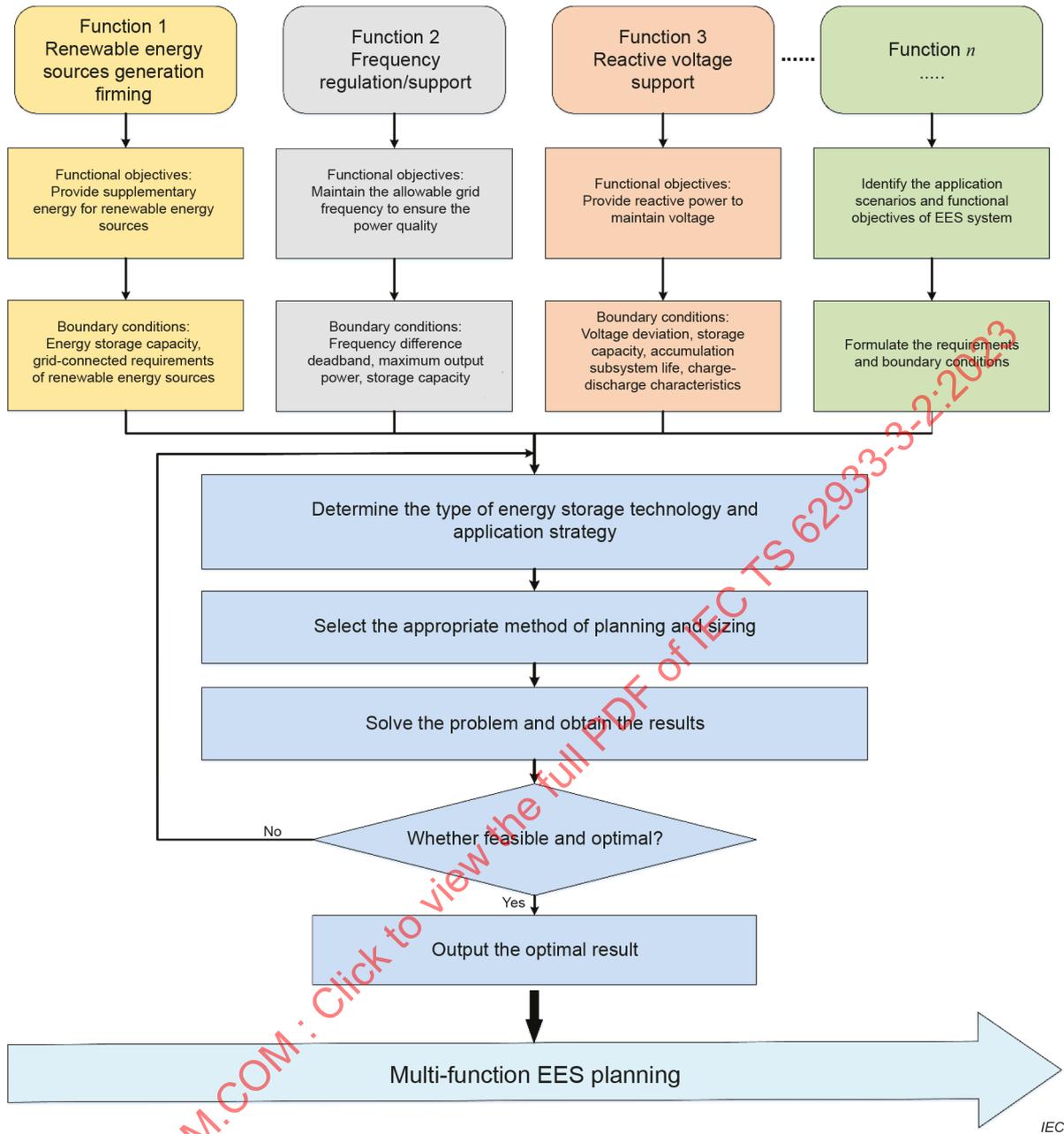
Figure 4 – Example of EES planning process with multi-function applications

Typical multi-function applications of EES systems are shown in Table 1.

Table 1 – Typical multi-function applications of EES systems

Application functions	Typical scenarios				
	Renewable energy sources integration	Power generation side	Transmission and distribution side	User side	Microgrid with distributed generators
Frequency regulation	√	√	√	√	
Reactive voltage support	√		√		
Voltage sag mitigation				√	
Output power firming	√				√
POD	√	√	√		√
Peak shaving		√	√	√	
Black start		√			√
Backup power supply		√	√	√	√

4.4.3 Characteristics and restrictions of the EES systems

4.4.3.1 General

The results of the sizing of EES systems are characteristic values and parameters of the EES system. The relevant parameters shall be given in a data sheet and should provide the following information:

- rated and nominal voltage
- rated and nominal frequency
- power capabilities
  - rated active input and output power
  - rated apparent power
  - rated reactive power
  - rated power factor
  - rated charging time
  - rated discharging time
  - short-duration active input and output power
  - short-duration reactive power
  - maximum change in power per time unit
  - power density (per mass/per volume)
  - access time (time between power demand and release of 50 % of the stored energy)
- step response performances
  - step response time
  - response time parameters
  - ramp rate
  - settling time

- energy capacity values
  - rated energy capacity at the beginning and end-of-service life
  - (energy capacity for rated active input/output power at the POC)
  - energy density (per mass/per volume)
  - depth of charge
  - depth of discharge
  - energy stored on investment
- energy efficiency values
  - rated roundtrip efficiency at the beginning and end-of-service life
  - (roundtrip over the entire rated energy capacity with rated active input/output power at the POC)
- accumulation subsystem
  - "installed energy capacity" with regard to capacity measurement procedures of the accumulation subsystem
  - self-discharge rate
- auxiliary subsystem
  - auxiliary power consumption
  - rated frequency of the auxiliary subsystem
  - rated power factor of the auxiliary subsystem
  - rated voltage of the auxiliary subsystem
  - rated apparent power of the auxiliary subsystem
  - rated energy consumption of the auxiliary subsystem
  - rated stand-by energy consumption of the auxiliary subsystem
- service life values
  - end-of-service life values
- usage (design basis)
  - duty cycle
  - duty cycle roundtrip efficiency at end-of-service life
  - recovery time
  - (equivalent) full cycles per day/year
  - expected service life
  - the cycle resistance
- reference environmental conditions
  - ambient temperature range
  - humidity
- point of connection
  - primary POC
  - auxiliary POC

In general, a rated value of a quantity is used for specification purposes, established for a specified set of operating conditions of a component, device, equipment or system. When specifying the rated values for planning purposes of an EES system, the critical operating limits of the power capability chart, capability reductions due to ageing, altered environmental conditions and other limiting factors shall be taken into account. All rated values used for planning purposes shall be values related to the end-of-service life.

Auxiliary power consumption can vary throughout the service life of the EES system and shall therefore be assessed for the whole service life of the unit and for the environmental conditions expected at the installation site. The influence on the overall EES system efficiency of the extreme weather conditions should also be considered.

End-of-service life value definitions are given in IEC TS 62933-1. The test of auxiliary power consumption is included in IEC 62933-2-1.

4.5 Service life of the EES systems

4.5.1 General

Subclause 4.5 deals with the operational lifetime of EES systems, including initial and ongoing performance assessments, as well as monitoring, maintenance, diagnostic and decommissioning aspects.

4.5.2 Installation

The installation of EES systems is typically technology dependent, for example safety requirements for electrochemical EES systems in IEC TS 62933-5-2. Remarks regarding the installation of EES systems are also given in IEC TS 62933-3-1.

There can be some site-specific regulations such as:

- legal and specific construction regulations;
- local regulations on minimum distances to residential buildings and roads;
- electrical regulations (e.g. the minimum electrical clearances or provision of adequate earthing points, insulation, electrical shielding);
- the standards for the installation of electrical equipment (e.g. for cables and terminals);
- legal and specific safety regulations;
- legal and specific environmental regulations;
- ensuring accessibility for persons and vehicles;
- if necessary, provision of access and space for maintenance and service work (including storage space for safety equipment);
- service conditions;
- if necessary, installation of access restrictions and controls (e.g. security to prevent accessing from the unauthorized persons or from unauthorized data exchange (cyber security));
- if required, usage of non-combustible and/or limited combustible materials (e.g. in accordance with ISO 5660-1);
- if necessary, installation of an appropriate fire extinction/detection system;
- possibly separation of subsystems (e.g. battery room separated from other electrical equipment);
- if necessary, integration of adequate air conditioning systems; it can be necessary to comply with technology-specific features, for example for battery systems.

4.5.3 Performance assessment

4.5.3.1 General requirements

The system supplier shall provide the necessary information about the EES system. This ensures that potential users (such as a utility) could have enough information to assess the performances of a system. Maintenance requirements and end-of-service life values shall be provided and compatible with the application.

The performance assessment of grid connected EES systems can include testing regarding rated input and output power, energy capacity, response times, energy and PCS efficiency, power control ability, frequency or voltage response, power quality support, protection and reconnection functionality, etc.

IEC 62933-2-1 deals with testing of EES systems.

4.5.3.2   Site acceptance test (SAT)

According to IEC TS 62933-1 the site acceptance test (SAT) is an on-site activity to demonstrate that the EES system is in accordance with the applicable system specifications and installation instructions.

There can be factory acceptance tests (FATs) before the site acceptance test. According to IEC TS 62933-1 a factory acceptance test (FAT) is a factory activity to demonstrate that the EES system, subsystems, components and additionally supplied systems/devices are in accordance with the specifications.

4.5.3.3   Periodic and event-based performance assessment

Periodic tests and checks should be performed, which can include:

- test of the monitoring functionality;
- inspection and recording of the operation conditions of functions of the EES system such as rated power and energy capacity, charge and discharge characteristics, response time, energy efficiency, etc., under the actual demand;
- partial and complete inspection of general and special protection functions of the EES system;
- inspection for the operating environment of the EES system (e.g. fire control system, ventilation system, lighting system, and temperature regulation system).

After renewal, modernization or upgrade of the EES system the SAT or some tests that have been agreed upon shall be performed again. In addition to the routine test items, other functional tests can be conducted, for example regarding frequency regulation, emergency backup/black start, voltage regulation or power quality support.

4.5.4   Operation and control

4.5.4.1   General

If an EES system is connected to a power grid, the EES system operation has to comply with regulations regarding grid operation and required safety functions. The EES system shall meet the grid code requirements.

4.5.4.2   Active power control

Grid-connected EES systems participating in grid dispatching should follow the principles of hierarchical control and unified dispatching and control their charge and discharge power in accordance with the instructions of the grid dispatching agency. The expected operation profile should be related to the agreed duty cycle. Recovery times should also be provided by the grid operator. The EES system shall meet the requirements regarding response time.

If grid-connected EES systems participate in frequency or voltage regulation or other ancillary services in accordance with the instructions of the grid dispatching agency, their response time regarding active power shall not be greater than pre-defined values.

For EES systems participating in emergency power support, the system power support should be provided in accordance with the instructions of the grid scheduling agreement or grid dispatching agency in the event of local grid failure and power outage. In case of an emergency, the full active power output run time should not be shorter than a pre-defined time (e.g. 15 min or 30 min). The grid dispatching agency may directly limit the amount of exchange power between the EES system and the grid.

Regarding active power output of the EES system, the deviation between the set value and actual value should not exceed a pre-defined value (e.g. 2 %).

4.5.4.3   Reactive power control

The power factor of the grid-connected EES system shall meet the power quality requirements.

When the EES system has to regulate both active and reactive power, there shall be an agreement about the priorities, for example the active power shall have a higher priority than the reactive power.

If grid-connected EES systems participate in grid voltage regulation in accordance with the instructions of the grid dispatching agency, their response time regarding reactive power shall not be greater than a pre-defined value (e.g. 200 ms, 10 cycles).

Regarding reactive power output of the EES system, the deviation between the set value and the actual value should not exceed a pre-defined value (e.g. 5 %).

4.5.4.4   Emergency response in case of EES system failure or grid fault

In the case where the EES system is found in an abnormal operating or emergency condition, the causes shall be investigated, and appropriate measures shall be taken to ensure the safety of the equipment.

There can be two different emergency response plans:

a) In case of abnormal operating conditions:

- The EES system shall stop due to a system failure in the power system; operations shall be executed in accordance with the dispatching instructions.
- If any abnormality such as alarm or protection actions occurs during the operation of the EES, all components of the EES system shall be inspected one by one to ensure the integrity of the EES system.
- When warning signals are triggered, the EES system shall not be shut down immediately; instead, real-time monitoring of the EES system operation shall be performed and on-site inspection and handling shall be organized.

b) In case of accidents:

- In the case of serious errors during operation (e.g. fire, explosion, natural disaster), it is recommended to execute an emergency stop and disconnect the circuit breaker; inform the responsible persons in accordance with local regulations.
- Organize relevant personnel to perform on-site inspection and take actions in accordance with the incidents, which can include:
  - checking all equipment, detecting broken parts and repairing or replacing these parts;
  - checking communication interfaces;
  - performing routine tests;
  - checking whether important operating parameters (such as charge and discharge current, voltage, temperature and other parameters) went beyond the normal range;
  - checking whether the fire control system sent a fire alarm;

– checking whether there are smoke or burn marks in the equipment;

– checking whether the accumulation subsystem is damaged or has error alarms;

– checking whether the control subsystem is damaged or presents errors.

4.5.5 Monitoring

4.5.5.1 General

The monitoring data shall be provided periodically or on request to the power grid operation system. The monitored data shall be logged either on event or periodically. The monitored data shall be collected, sorted and analyzed periodically to decide about possible service or maintenance. Annex B provides further information about the default assignment of permissions to roles within different monitoring and maintenance states.

4.5.5.2 Monitoring the power grid

The following parameters concerning the power grid shall be monitored:

- voltage and current of the POC;

- active and reactive power exchanged between the EES system and the utility grid.

4.5.5.3 Monitoring the switching devices

The monitoring system shall meet the requirements of the power grid communication concerning relay protection, automatic safety devices, automation systems, dispatching devices and other services. The data of the switching devices to be monitored include:

- the transformer tap changer position, the switching status of circuit breakers inside the EES;

- the main transformer tap changer position, the switching status of circuit breakers at the POC.

4.5.6 Maintenance

4.5.6.1 General

Besides servicing, repairing or replacing of necessary parts maintenance involves also functional checks. The general maintenance requirements include:

- checking and recording the data uploading and downloading communication between the energy storage management subsystem and each subsystem to verify that they are properly functioning;

- checking the alarm and protection actions;

- checking the communication system function to ensure satisfactory communication with the upper-level control system;

- checking if the EES system and its subsystems indicate normal functioning and work properly, for example by checking alarms and warnings and checking the communication exchange;

- inspecting the subsystems of the EES system (management, accumulation and power conversion subsystem) periodically according to technology dependent specifications;

- keeping the subsystems correctly and firmly connected and reliably grounded;

- ensuring all the operation metrics and measured values of EES system and its subsystems are within the normal range;

- ensuring that the environmental conditions (e.g. ambient temperature and humidity) meet the operation requirements of each subsystem;

- taking corresponding measures in time for inspection and treatment in case of abnormal operation or failure;

- collection, analysis and inspection of EES system data;
- inspection of EES system control and regulation functions:
    - routine test;
    - test after overhaul and upgrade;
    - inspection of EES system protections;
    - inspection of operating environment of the EES system;
- replacement of equipment whose service life has expired or will soon expire.

4.5.6.2   Regular maintenance

Regular maintenance of the EES system shall include:

- maintenance and operation tests of the EES system shall be carried out by referring to the manufacturer's manual, etc., with appropriate techniques and cycles;
- maintenance plans (inspection, commissioning) shall be established and include maintenance items;
- a maintenance report shall be prepared including:
    - date of creation of maintenance report;
    - responsible person(s);
    - periodical maintenance items;
    - documentation of executed maintenance works (visual inspections, installation status maintenance, protection status maintenance);
    - records of all inappropriate conditions, including any replacement parts, and corrective actions taken.

The EES system supporting the backup power supply should be operated with an isolated mode from the electrical grid once a month to ensure the operation reliability.

4.5.6.3   General maintenance requirements for accumulation subsystem

General maintenance requirements for the accumulation subsystem shall include the following items:

a) General:

- The accumulation subsystem shall have a complete nameplate provided by product manufacturers.
- The racks placed on the accumulation subsystem shall be free of deformation. The metal rack and the base shall be reliably grounded. The grounding connection shall be tightly fastened and its resistance shall be verified.
- The main circuit of the accumulation subsystem shall be connected correctly and firmly, and the heat dissipation/auxiliary heat device shall operate normally.
- The accumulation subsystem shall be equipped with complete protective functions. Before the charging-discharging of the accumulation subsystem, the corresponding protection requirements such as threshold value shall be determined.

b) Patrol inspection:

- The accumulation subsystem room or prefabricated cabin shall be ventilated in advance before personnel on duty enter the accumulation subsystem building or prefabricated cabin.
- The temperature and humidity of the accumulation subsystem or prefabricated cabin shall be within the operating range. The lamp equipment is intact and operational.
- The temperature control equipment such as HVAC shall be in the operational range.
- The insulation of live parts shall be checked.

- The grounding of the metal enclosure and support shall be checked.
- The ventilation facilities shall be checked.
- The secure workspace shall be checked.
- The lighting equipment shall be checked.

c) Abnormality and fault handling:

- When the accumulation subsystem is over-discharged and over-charged, short-circuited, etc., it shall be stopped for inspection.

- When the voltage of the accumulation system is outside the manufacturer's specified limits then the necessary corrective actions shall be implemented as specified by the manufacturer for such cases. No ad-hoc charges or discharges shall be implemented as this can lead to catastrophic failures. When the accumulation subsystem, especially the battery based system, is repeatedly charged/discharged, the voltage difference among components of the accumulation subsystem (i.e., battery cell/module in battery system) tends to exceed the tolerable value. Therefore, it is necessary to re-balance the voltages. In the battery-based system, a cell voltage balancing process is necessary.

- When an abnormal situation such as smoke, fire or explosion occurs in the accumulation subsystem, the surrounding personnel shall be evacuated in time, and corresponding measures shall be taken immediately in accordance with the emergency plan; the failure shall be prevented from expanding and reported in time.

4.5.6.4 Specific maintenance requirements in terms of EES technologies

Related maintenance requirements are provided in Annex C.

4.5.6.5 Specific maintenance requirements for power conversion subsystem

a) General:

- The power conversion subsystem shall have a complete nameplate provided by the product manufacturers.

- The housing of the power conversion subsystem should have a standard grounding mark. The metal bracket and the base shall be reliably grounded. The grounding connection shall be tightly fastened and its resistance should be verified.

- The power conversion subsystem shall have a complete protective function. Before it starts operating, the corresponding protection requirements of the power conversion subsystem shall be determined.

b) Patrol inspection:

- The AC/DC voltages and currents of the power conversion subsystem are within the operational range.

- The indicator lamp and power supply lamp of the power conversion subsystem are intact and operational.

- The human machine interface (HMI) of the power conversion subsystem does not indicate any error and there is no hardware and configuration alarm information.

- The operation mode of the power conversion subsystem and the switching position of the selection switch are set correctly.

- The indoor temperature of the power conversion subsystem is within the operational range.

- The lighting equipment and the exhaust system are operating.

- The cooling system and the uninterruptible power supply of the power conversion subsystem work correctly without abnormal noise.

- The insulation of live parts shall be checked.

- The grounding of the metal enclosure and support shall be checked.

- The ventilation facilities shall be checked.

- The secure workspace shall be checked.

- The lighting equipment shall be checked.

c) Abnormality and fault handling:

- The power conversion subsystem shall be shut down immediately in case of any fault or failure to inspect and handle the failure. The corresponding records shall be recorded and reported to the relevant person in charge. Records include, but are not limited to, fault case and codes, equipment model and number, and the fault time.

- When the control subsystem of the power conversion subsystem works abnormally, it shall be stopped for inspection.

- When the power output of the power conversion subsystem is out of operational range, the power component, control drive module and the control communication channel shall be stopped for inspection.

- The fault treatment of the power conversion subsystem shall be opened after some marginal time of power failure (e.g. 30 min) for the sake of safety.

4.5.6.6   Specific maintenance requirements for management subsystem

a) General:

- The measurement acquisition lines such as temperature, current, voltage, etc., of the management subsystem are connected reliably, without looseness or falling off.

- The working status indicator and monitoring interface of the management subsystem work without alarm.

- The alarm management, protection, charging/discharging control and other configuration parameters of the management subsystem shall be set in accordance with the approved parameter value lists. When the configuration parameter values need to be changed, the configuration parameter list should be re-released and executed by the on-duty personnel with operational authority.

- The management subsystem communicates with the power conversion subsystem and monitoring system without communication error.

b) Patrol inspection:

- The indicator lamp and power supply lamp of the management subsystem are intact and operational.

- The temperature, current, voltage and other measured values of the management subsystem shall be within the operational range without alarm.

- The charging status of the accumulation subsystem is within the operational range.

c) Abnormality and fault handling:

- When the management subsystem has a communication failure, the communication cable shall be checked to verify whether it is loose or has poor contact.

- When the management subsystem shows alarm and protection action signals during operation and cannot be reset, it shall be stopped for inspection.

- When the management subsystem fails, the server of the management subsystem and power module shall be checked.

5 Frequency regulation/control

5.1 Primary and secondary frequency regulation

5.1.1 Applications of the EES systems

5.1.1.1 Functional purpose of the EES systems

The EES system has the capability to actively support grid frequency by discharging or charging for up to short- and mid-term durations (e.g. 30 s and 15 min). When the frequency is dropping below its desired setpoint, the EES system will reduce the charging power or increase the discharging power to counteract or partially mitigate the frequency deviation, to support the grid frequency, with part or the whole of its active power capabilities. Conversely when the frequency is rising above the desired setpoint, this can be counteracted or partially mitigated by increasing the charging rate or reducing the discharge rate of the EES system.

5.1.1.2 Application related requirements

Most of electrical power system operators have defined frequency regulation as primary and secondary frequency regulation. The primary frequency regulation of the EES system means that once the frequency of the power grid deviates from the rated value, the control system automatically controls the increase or decrease of the active power of the energy storage, limits the frequency change of the power grid, and maintains the automatic control process of the grid frequency. The EES system participates in the secondary frequency regulation, which is to receive and track the load instructions issued by the dispatching authority. The activation and duration can differ from country to country and are usually defined by the grid codes. The block diagram of the frequency control and the schematic diagram of their time or duration are shown in Figure 5 and Figure 6.
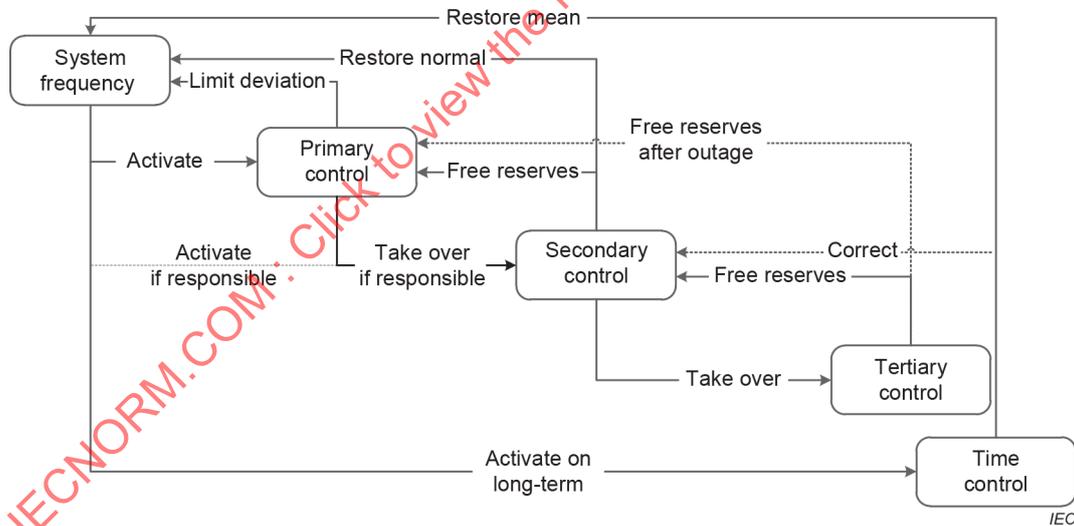
Figure 5 – Example of frequency control block diagram
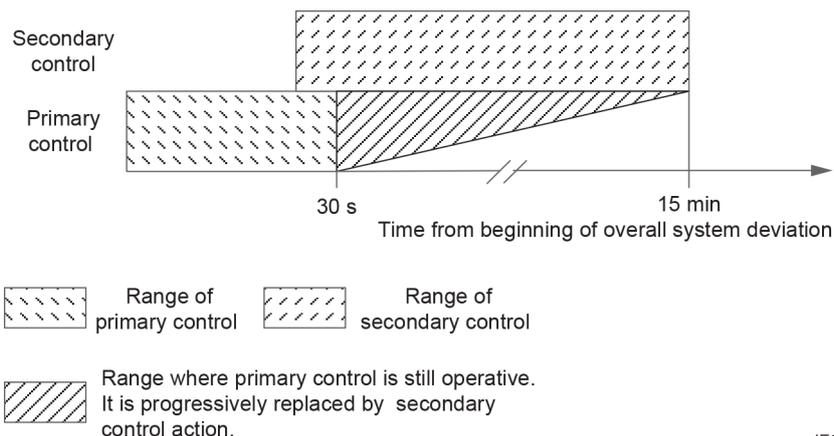
Figure 6 – Example of frequency regulation time/duration schematic diagram

In the frequency regulation applications, in addition to the application requirements listed in 4.1.2, the following requirements shall be considered.

a) Full response time

   The full primary reserve response time of the EES system means the time period between the occurrence of frequency deviation and the corresponding activation of the reserve. The response time describes how fast the system can respond to change.

   It is mandatory not to exceed 30 s in the ENTSO-E.

b) Activation delay

   The activation delay means the period of time between the occurrence of frequency deviation and the instant when the power has increased/decreased by 5 % of the requested power.

c) Activation period

   The activation in the normal state is continuous. When the frequency of the electrical system is in the alert state and emergency state, the activation period of the primary reserve shall be defined by each system operator. It shall typically be greater than or equal to 15 min, but less than or equal to 30 min.

d) Ramping time

   The ramping time means the time necessary to increase/decrease the power from 5 % to 95 % of the requested power.

e) (Rated) short-duration input and output power

   Subclause 4.1.2.2 is applicable.

NOTE   Three frequency states of the electrical system can be defined as:

1) The frequency of the electrical system is in the normal state when:

   – the absolute value of the frequency deviation from the nominal frequency f_n is less than 200 mHz;

   and

   – the absolute value of the frequency deviation has not been higher than 50 mHz for more than 15 min and has not been higher than 100 mHz for more than 5 min.

2) The frequency of the electrical system is in the alert state when:

   – the absolute value of the frequency deviation from the nominal frequency f_n is less than 200 mHz;

   and

   – the absolute value of the frequency deviation has been higher than 50 mHz for more than 15 min or has been higher than 100 mHz for more than 5 min.

The end of the alert state, that is to say the return to normal state, happens as soon as the absolute value of the frequency deviation is lower than 50 mHz.

3) The frequency of the electrical system is in the emergency state when:
   – the absolute value of the frequency deviation is higher or equal to 200 mHz.

5.1.2   Conditions and requirements for connection to the grid

Subclause 4.2 is applicable.

5.1.3   Design of the EES systems

5.1.3.1   Structure of the EES systems

The EES system structure and components defined in 4.3.2 are also applied to the frequency regulation applications. In addition, more elements need to be considered. EES systems for frequency regulation applications can be installed in conjunction with a generator, in order to improve the effectiveness of frequency regulation applications. A typical configuration of EES systems in conjunction with a generator is shown in Figure 7.

The primary frequency regulation of the EES system is achieved automatically based on the grid frequency. When the grid frequency drops or rises, the EES system increases or decreases the power exchange, so as to ensure that the grid frequency is maintained within the allowable range.

In the dispatch control mode, the active power variation of the secondary frequency regulation of the EES system is automatically set by the dispatching automatic generation control (AGC) through the supervisory control and data acquisition (SCADA). When the set power changes, the EES system central controller sends a power adjustment command, and the EES system releases or absorbs the active power specified by the scheduling to complete the active power change of the secondary frequency regulation.
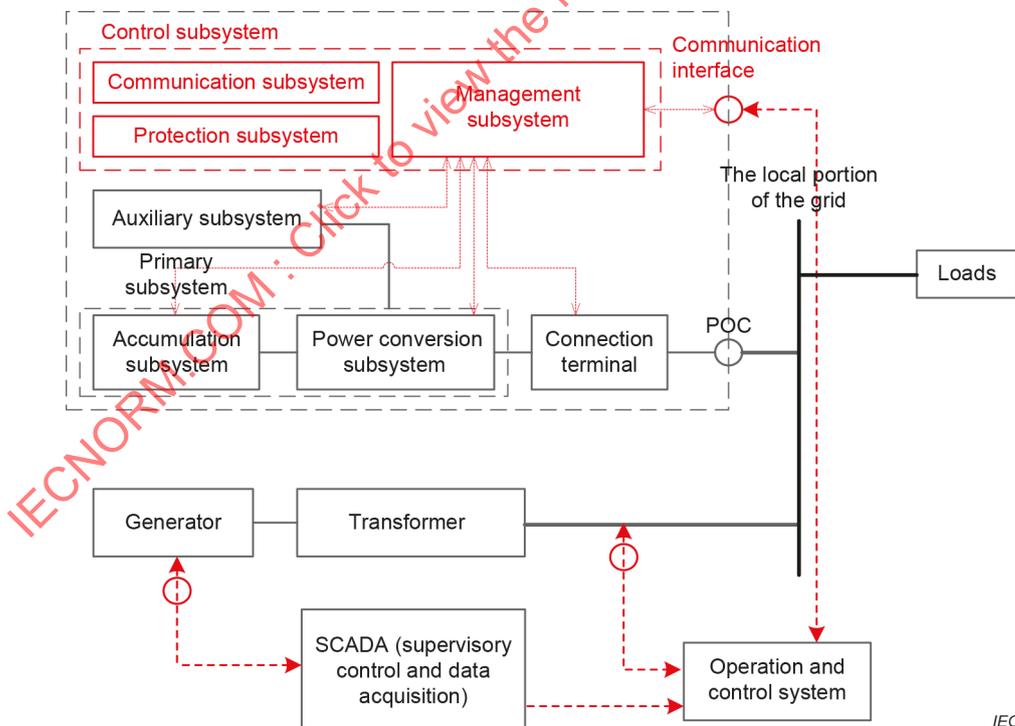
Figure 7 – Example of the system structure of the EES system for frequency regulation in conjunction with generator

5.1.3.2   Subsystem specifications

Subclause 4.3.3 is applicable.

5.1.3.3 Grid integration of the EES systems

Subclause 4.3.4 is applicable.

5.1.3.4 Operation and control

a) Droop control mode

The primary frequency regulation is mainly performed by the droop control shown in Figure 8.
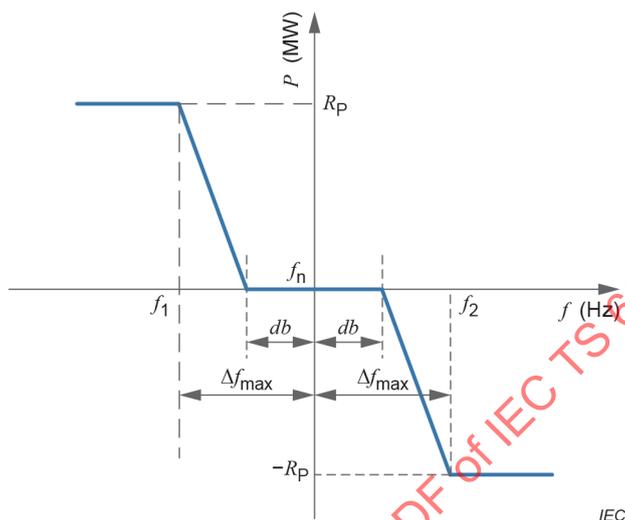
Figure 8 – Example of droop control with frequency dead band

NOTE   An active power reserve R_P, called "primary reserve", can be used upward or downward by the system operator.

The EES system shall be equipped with a primary frequency regulator. In this control mode, the variation in active power output of the EES system is proportional to the negative frequency deviation. It reduces as the frequency increases based on the following control formula which uses the active sign convention (a positive value of P corresponds to a power injection whereas a negative value of P corresponds to a power absorption):

$$P - P_C = -K_1 \times \left(f - \left(f_n \pm db \right) \right)$$

where

P is the output active power of the EES system (MW);

P_C is the active power set point of the EES system at nominal frequency f_n (MW);

f is the frequency measured on the grid (Hz);

f_n is the nominal frequency (50 or 60 Hz);

K_1 is the proportional gain for the $P(f)$ characteristic of the EES system (MW/Hz);

db is the dead band of the primary frequency regulation. It shall be adjustable and set to 0 eventually.

The droop control may include an intentional dead band corresponding to a frequency band in which there is no change in active power injection as a result of changes to the frequency that are within the dead band. The value of this dead band shall be adjustable.

The proportional gain K_1 of the EES system shall be adjustable. It shall be comprised between a minimum value $K_{1,\min}$ and a maximum value $K_{1,\max}$ to be defined by the system operator. In operation, the values of the upward and downward gains can be different, and the value of each of the gains shall:

- guarantee the release of the entire primary reserve R_P made available by the EES system for any difference in frequency deviation amplitude greater than or equal to $\Delta f_{\max}$ (200 mHz recommended by ENTSO-E),

- when $f > f_n$ or when $f < f_n$

  – be constant at least on a time period of (15 to 30) min and remain consistent with the change in power setpoint;

  – be independent of the frequency variation.

Activation of the primary frequency regulation provision has to start as soon as possible after occurrence of the frequency deviation. However, an activation delay is almost unavoidable. It includes the time that the frequency monitoring device takes to detect a frequency deviation plus the time for instructing a response, and the time for the EES system to start delivering the MW change in output. To ensure that this activation delay remains within acceptable limits, a maximum value t_1 specified by the electrical system operator shall not be exceeded.

The EES system shall provide the primary frequency regulation service continuously and permanently in normal state. The related activated primary reserve capacity shall be equal to $\min(R_P, -K_1 \cdot \Delta f)$.

The time to full activation of the EES system shall not exceed a maximum value t_2 specified by the electrical system operator ($t_2 < 30$ s recommended by ENTSO-E for Continental Europe). The activation of the full primary reserve capacity shall rise at least linearly for under-frequency, and shall fall at least linearly for over-frequency.

The combined response of frequency regulation shall meet the following requirements:

– the activation of frequency regulation shall not be artificially delayed and begin as soon as possible after a frequency deviation;

– in case of a frequency deviation equal to or larger than 200 mHz, at least 50 % of the full frequency regulation capacity shall be delivered at the latest after 15 s;

– in case of a frequency deviation equal to or larger than 200 mHz, 100 % of the full frequency regulation capacity shall be delivered at the latest after 30 s;

– in case of a frequency deviation equal to or larger than 200 mHz, the activation of the full frequency regulation capacity shall rise at least linearly from 15 to 30 s;

– in case of a frequency deviation smaller than 200 mHz, the related activated frequency regulation capacity shall be at least proportional with the same time behaviour referred to in the above four points.

NOTE See Commission Regulation (EU) 2017/1485 in the Bibliography.

b) Secondary frequency regulation

Secondary frequency regulation is performed by the electrical system operator through the use of an automatic generation control (AGC) software. AGC computes the area control error (ACE) of a balancing area from interconnection load flows and frequency measurements.

According to the different ways of ACE signal expression, the ACE signal can be divided into FFC, FTC and TBC. TBC is currently the most commonly used control mode, which can ensure the dual stability of frequency and tie-line, and is more suitable for modern interconnected power systems. Each area uses the value of ACE to adjust the output commands of the frequency regulation units in the area to ensure that the power generation and load of the system are in balanced state.

In order to minimize its ACE and maintain the power grid frequency close to its nominal value f_n, the electrical system operator has to continuously regulate supply or demand. For this purpose, the AGC software sends a frequency regulation power setting signal to all energy resources contributing to the secondary frequency reserve (generators, EES systems, demand response). The EES system shall adjust its active power provision accordingly.

Secondary frequency regulation means that EES systems shall provide sufficient adjustable capacity and a certain ramp rate. During the operation of AGC, the primary frequency regulation shall still be enabled.

5.1.3.5 Communication interface

Subclause 4.3.8 is applicable.

5.1.4 Sizing and resulting parameters of the EES systems

5.1.4.1 Sizing

a) Sizing process of the EES system

The general sizing process of the EES system for frequency regulation is shown in Figure 9 and Figure 10.
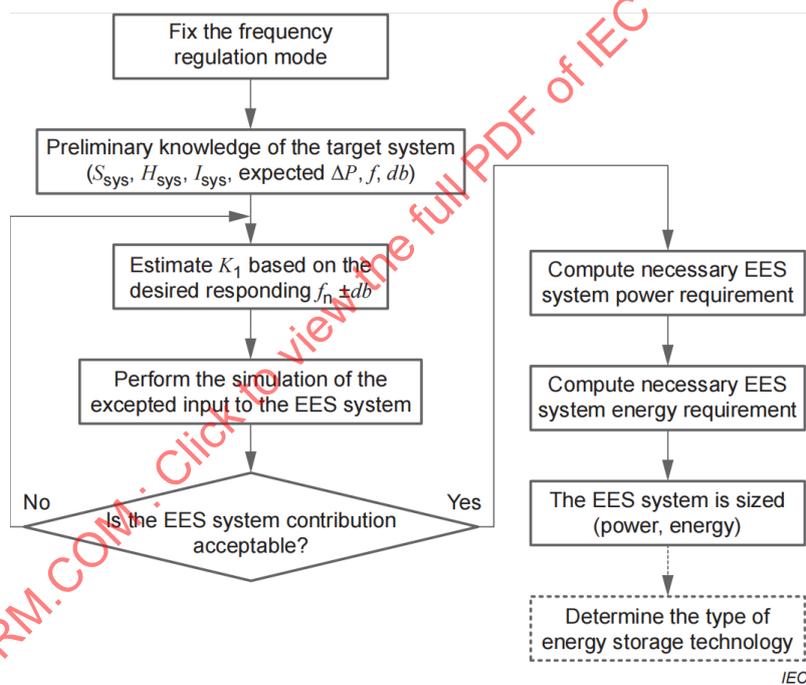
**Figure 9 – Example of EES system sizing process
for primary frequency regulation**
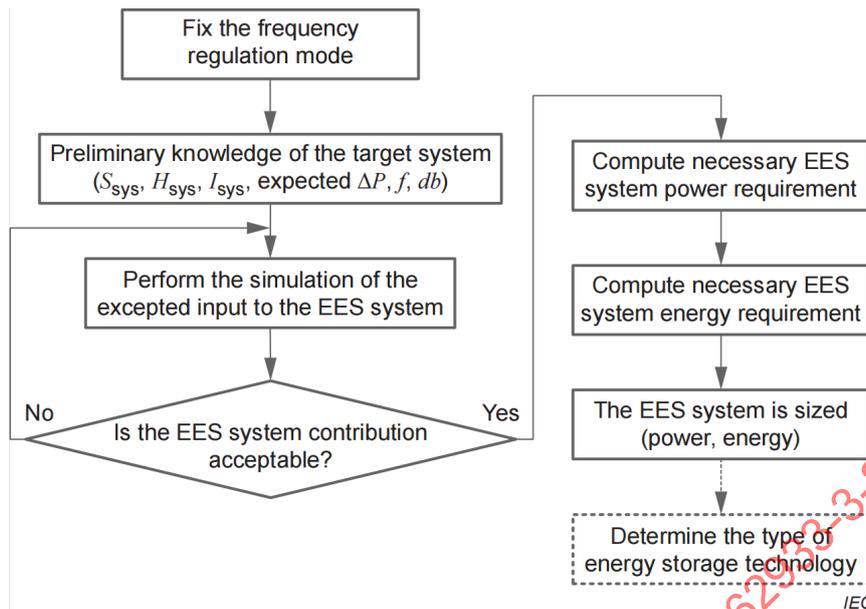
**Figure 10 – Example of EES system sizing process
for secondary frequency regulation**

In Figure 9, the method uses the preliminary knowledge of the target system, namely system size (S_{sys}), system inertia (H_{sys}), and power/frequency characteristic (I_{sys}). The user shall decide the target power (ΔP) unbalance for which the EES system is going to be sized.

In addition, if the EES system participates in both primary and secondary frequency regulation, the method of sizing should be different. In order to ensure that the EES system can smoothly adjust the frequency, the power should be the maximum power required in the primary and secondary frequency regulation. The selection of energy capacity is the sum of the capacity required for the primary frequency regulation and the secondary frequency regulation.

b) Requirements for sizing

When sizing the EES system for frequency regulation applications, it is necessary to consider not only the constraints of the system operating state, but also the constraints of energy storage charging and discharging power and capacity.

- In order to avoid the EES system charging or discharging frequently, the dead band of the frequency regulation using the conventional generators is for reference.

- In the power output stabilization time of the primary frequency regulation, the maximum output power is the rated power of the EES system or the short duration input/output power, if applicable.

- To configure the capacity of the EES system for frequency regulation, the active power output of the conventional generators is for reference, and the capacity of the EES system shall meet the needs of frequency up-regulation and down-regulation at any time.

- The EES system is energy limited. Owing to the finite capacity of its accumulation subsystem, there exists the risk of losing effective frequency regulation capacity in case of long-term deviations of the system frequency. Thus, the management of the energy is essential for guaranteeing continuous activation particularly in stressed system states.

5.1.4.2   Characteristics and restrictions of the EES systems

Subclause 4.4.3 is applicable.

5.1.5 Service life of the EES systems

5.1.5.1 Installation

Subclause 4.5.2 is applicable.

5.1.5.2 Performance assessment

Subclause 4.5.3 is applicable.

5.1.5.3 Operation and control

a) Primary frequency regulation

As shown in Figure 8, if the frequency of the power grid is within the dead band, the EES system does not participate in frequency regulation. Δf_{max} is the maximum allowable frequency deviation. When the frequency value is between f_1 and the minimum value of the dead band, the EES system reduces the charging power or increases the discharging power according to the frequency droop curve. When the grid frequency is between the maximum value of the dead band and f_2, the EES system increases the charging power or decreases the discharging power according to the frequency droop curve. When the grid frequency is lower than f_1 or higher than f_2, the EES system activates the full power reserve. The operation and control process are shown in Figure 11.
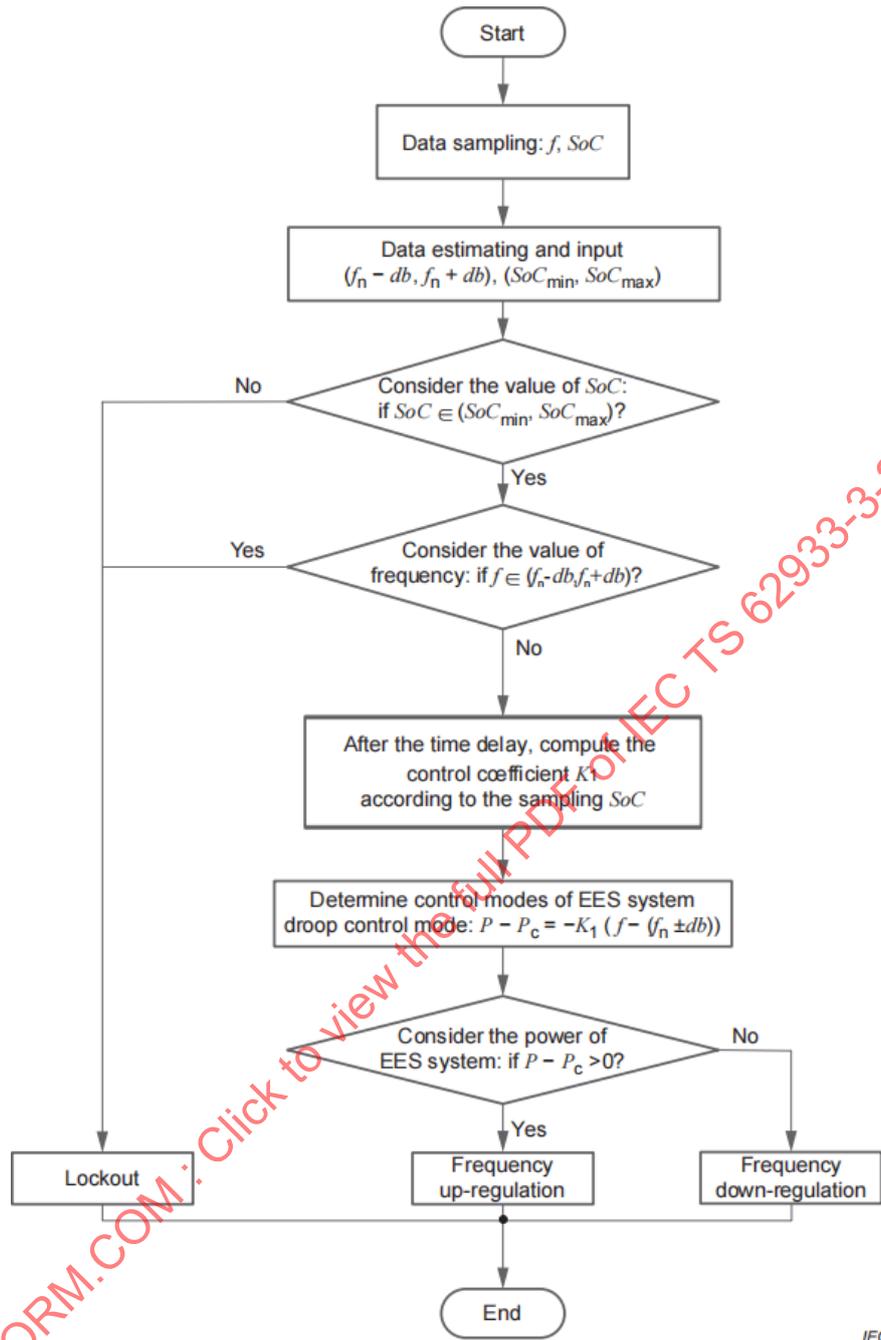
Figure 11 – Example of control strategy of the EES system participating in primary frequency regulation

NOTE   The idling SOC of the EES system can be set to 50 %, allowing the EES system to participate in both frequency up-regulation and down-regulation services. K_1 is the gain of the EES system corresponding to the primary frequency regulation, and it will be adjusted according to the actual SOC of the EES system.

The capability of an EES system to participate in primary frequency regulation is characterized by:

– an active power reserve R_P, called "primary reserve", that can be used upward or downward by the system operator;

– a control strategy allowing the provision of the amount of reserve to be delivered when the frequency deviates from its nominal value f_n or from the specified dead band if any;

– a dynamic time (delay time, time to full activation, full activation period).

The primary reserves shall be activated as soon as possible after the detection of a frequency deviation from the nominal value f_n or from a specified dead band if any, without any control signal from the electrical system operator.

The various levels of SOC are presented in Table 2 and Figure 12.

Table 2 – Example of the definition of various states of charge

SOC levels	Definition
SoC_{sup}	Higher SOC threshold in normal state, allowing to release the primary reserve R_P downwards during t_3.
SoC_{inf}	Lower SOC threshold in normal state, allowing to release the primary reserve R_P upwards during t_3.
SoC_{max}	Higher limit SOC threshold in normal state, corresponding to a security constraint for the EES system.
SoC_{min}	Lower limit SOC threshold in normal state, corresponding to a security constraint for the EES system.
$SoC_{reserve\_max}$	SOC threshold above which the reserve mode is activated to manage the saturation of the storage.
$SoC_{reserve\_min}$	SOC threshold below which the reserve mode is activated to manage the exhaustion of the storage.

There is a hypothesis that $P_C = 0$ and no other services such as secondary frequency regulation are active at the same time, and that the EES system shall be able to maintain a full activation of the active power reserve for a minimum duration t_3 (15 min mandated by ENTSO-E for Continental Europe).
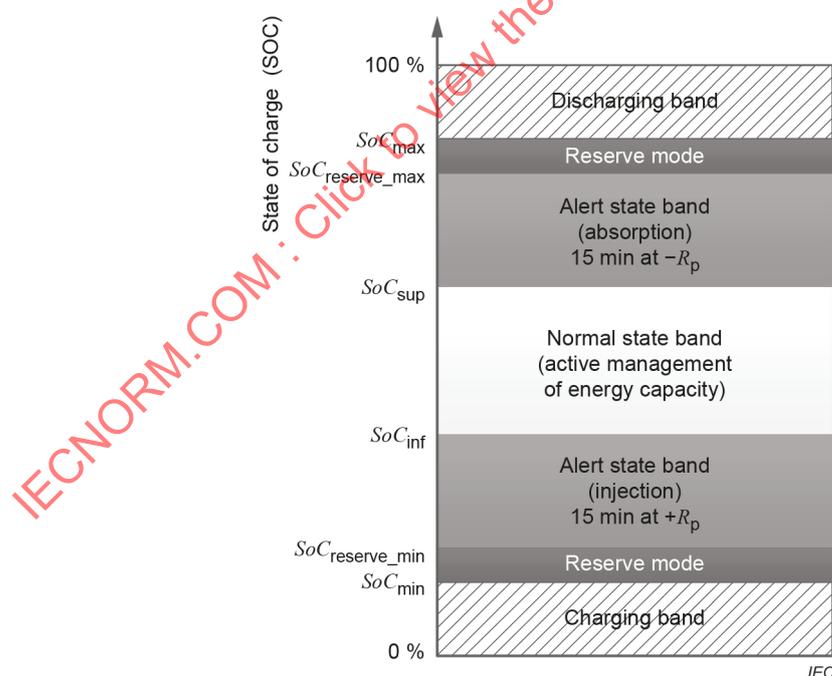
Figure 12 – Example of SOC thresholds and storage modes of the EES system

NOTE   0 % and 100 % are relative limits of the SOC, related to the capacity reserved for frequency regulation, not absolute limits of SOC. $SoC \in [SoC_{inf}, SoC_{sup}]$ can be defined as normal state band. $SoC \in [SoC_{reserve\_min}, SoC_{inf}]$ or $SoC \in [SoC_{sup}, SoC_{reserve\_max}]$ can be defined as alert state band.

In order to guarantee an energy reserve for primary frequency up-regulation and down-regulation over a duration t_3 corresponding to the full activation period, the EES system shall have a ratio E_{useful}/R_P higher than 2 t_3, where E_{useful} is the useful energy capacity (in kWh or MWh) of the EES system and it is the energy capacity to perform the primary reserve control.

The EES system shall provide the primary frequency regulation so long as the energy reserve is not exhausted or saturated. In order to guarantee the continuity of service and the availability of the energy reserve, an active management of the stored energy is necessary.

In order to allow simultaneously the active management of the stored energy and the provision of primary reserve, the maximum power in charge and discharge mode, respectively $P_{gen,max}$ and $P_{load,max}$, shall be higher than 110 % of the primary reserve R_P. The EES system is in the reserve mode whenever the SOC is above the threshold $SoC_{reserve\_max}$ or below $SoC_{reserve\_min}$ (see Figure 12).

In order not to limit the participation of the EES system to the primary reserve when changing the active power setpoint of the EES system, the maximum value of the active power set point $P_{C,max}$ shall be lower than or equal to $P_{gen,max} - R_P$ and $P_{load,max} - R_P$ at the same time.

The active management of the storage will have the capability to modify the active power setpoint P_C, so as to maintain the SOC in normal state allowing to release R_P upwards or downwards during t_3. This state of charge will have an upper and a lower limit, SoC_{inf} and SoC_{sup}, that guarantee the release of R_P upwards or downwards during t_3.

Some grid codes (e.g. RTE) will require dynamic limitations on the variations of P_C:

P_C is the constant over each infra-day market step (e.g. 15 min), which shall vary following a maximum ramp rate.

The objective is that P_C shall vary slowly compared to $K \cdot \Delta f$, so as not to counteract/neutralize the frequency regulation service.

In the case of a continuous variation in the setpoint power, the ramps (MW/min) shall be configurable and not lead to a change from 0 to the minimum setpoint power (or to the maximum setpoint power) in less than 15 min.

In the alert state or emergency state, the modification of the active power setpoint shall be avoided if this modification goes against the needs of the electrical system (for example, it has to be forbidden to modify the active power setpoint downwards towards if the frequency is below the nominal frequency f_n).

If the energy reserve is exhausted or saturated or when the reserve mode is activated, the EES system shall renew its energy reserve when the system frequency returns to the normal state until it is in the normal state band.

During the normal state band the EES system shall react to the normal frequency deviation while in reserve mode the EES system shall react only to the short-term frequency deviation. During the transition period from normal state band to reserve mode and vice versa, the EES system shall react to the combination of normal frequency deviation and short-term frequency deviation.

b) Secondary frequency regulation

When the EES system is required to absorb active power from the grid, the frequency regulation signal is sent to the operation and control system and then assigned to the accumulation subsystem and the PCS for control (see Figure 13), while energy is stored in the accumulation subsystem. Accordingly, when the EES system is required to release active power, the frequency regulation command is sent to the operation and control system and is assigned to the accumulation subsystem and the PCS. Energy is released by the EES system to the power grid. The operation and control process are shown in Figure 14.
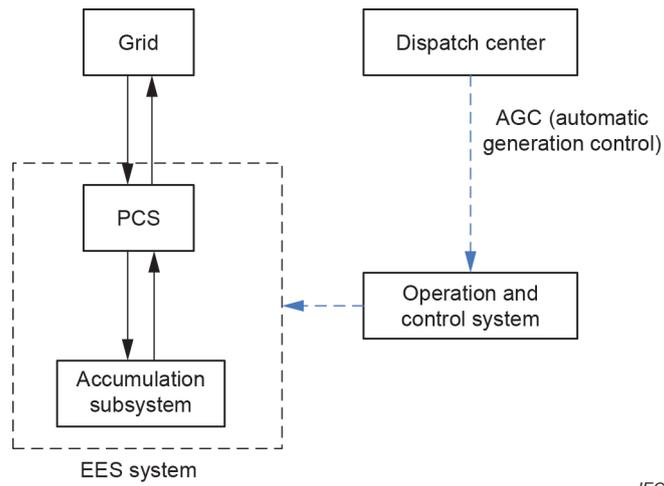
IEC

**Figure 13 – Example of EES system participating
in secondary frequency regulation**
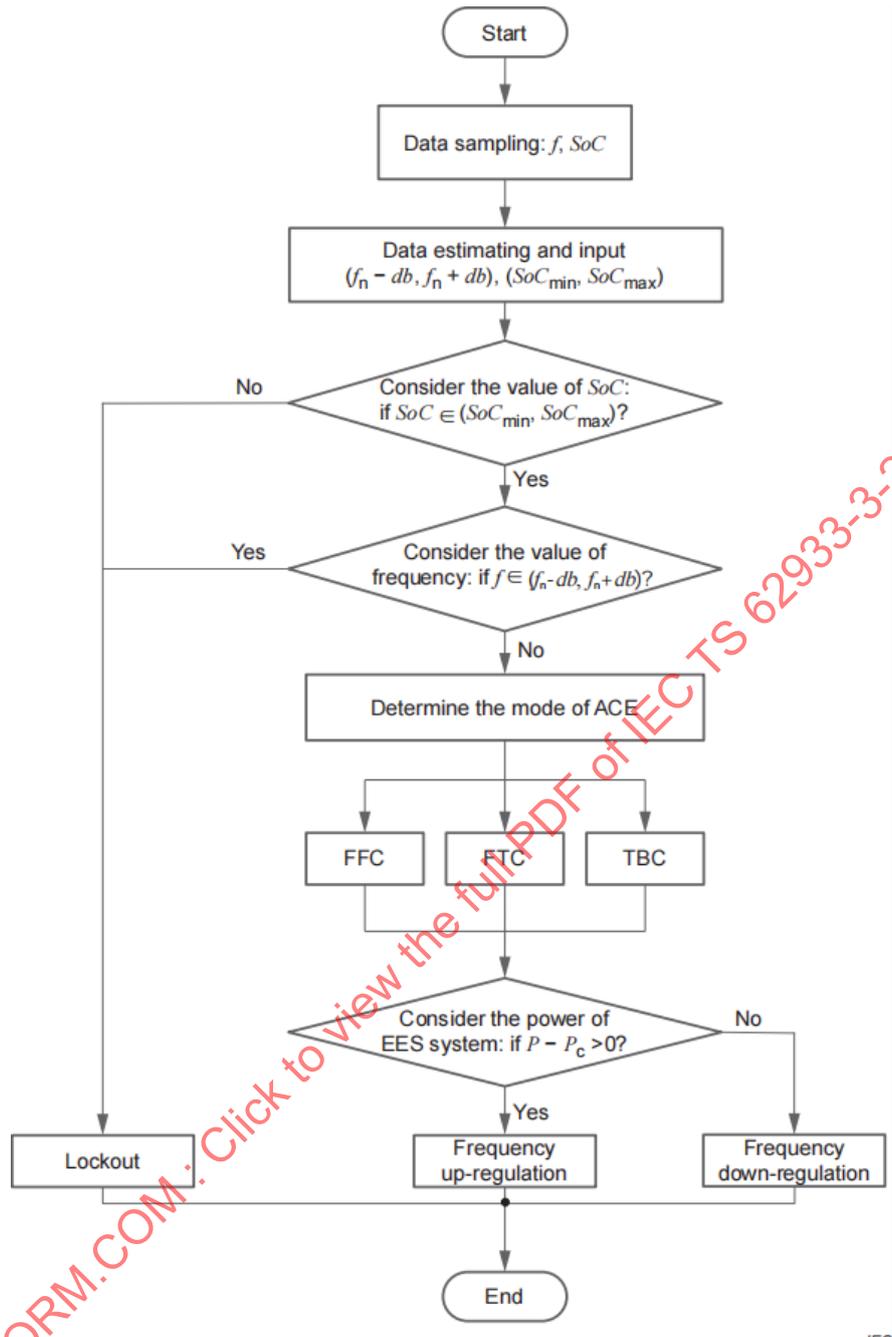
**Figure 14 – Example of control strategy of EES system
participating in secondary frequency regulation**

NOTE   The idling SOC of the EES system can be set to 50 %, allowing the EES system to participate in both frequency up-regulation and down-regulation services.

5.1.5.4   Monitoring

Data exchange is necessary for a good integration of the EES system in the electrical system at different time periods. The data exchanged, which depend on the importance of the EES system and its participation in ancillary services, shall be compatible and consistent with the remote control and communication systems used by the electrical system operator with the various players.

The conformity of systems dedicated to data exchange shall be verified against the performances specified by the electrical system operator.

The EES system shall have the basis of information network communication and the data collection capability of various types of equipment. The relevant data of the EES system shall have the ability to access the centralized monitoring and operation and maintenance platform.

When the EES system is used to regulate the grid frequency, the EES system shall operate automatically or remotely in accordance with the target in the scenario. The operating state of the EES system shall be monitored to check whether the remote signal and remote measurement of the EES system are normal.

The information of the voltage, current, active power, reactive power, state of charge, abnormal alarm and fault of the energy storage unit of the EES system shall be monitored. Information such as abnormal alarms of other equipment shall be monitored.

5.2 Fast frequency control

5.2.1 Applications of the EES systems

5.2.1.1 Functional purpose of the EES systems

The EES system has the capability to actively support grid frequency by discharging or charging quickly (e.g. within 100 ms). The fast frequency control of the EES system is to approximate the process of inertial kinetic energy throughput of traditional generators based on the rate of change of the frequency. The purpose is to slow down the rate of change of the frequency of the system during sudden failures, reduce the amplitude of the transient frequency difference, increase the system damping, and enhance the system stability.

Here fast activation time and ramp rate are very important. Furthermore, the amount of the active power is very important (high power density).

Since it is needed for a short time (bridging up to fully primary response), energy density is not important. The maximum active power response is typically needed for less than 15 min.

5.2.1.2 Application related requirements

In a conventional, power-balanced network, the grid frequency is stabilized close to the nominal frequency (e.g. 50 Hz or 60 Hz). If the generation power exceeds the load power, the grid frequency increases. If the generation power is less than the load power, the grid frequency decreases. Therefore, the EES system has the capability to support grid frequency by discharging or charging.

An example of frequency curve with fast frequency control is shown in Figure 15, which includes the first frequency swing.
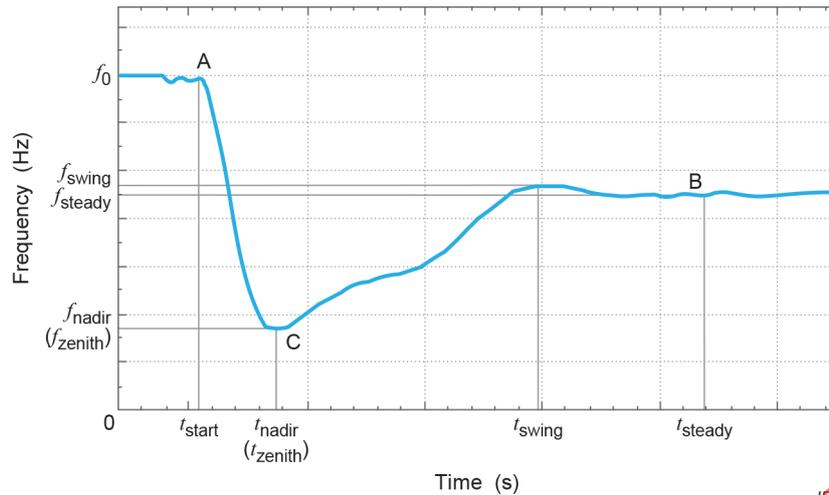
Figure 15 – Example of frequency curve with fast frequency control

The main parameters describing the first frequency swing are:

- f_0: frequency before disturbance;

- f_{nadir} (f_{zenith}): global minimum/maximum of the frequency;

- f_{steady}: steady state or settling frequency after disturbance;

- f_{swing}: frequency at which the first frequency swing ends;

- t_{start}: start of first frequency swing after disturbance;

- t_{nadir} (t_{zenith}): time of f_{nadir} (f_{zenith});

- t_{steady}: time when frequency reaches steady state f_{steady};

- t_{swing}: end of the first frequency swing;

- $ROCOF_{010}$: df over first 10 % of t_{nadir} (t_{zenith});

- $ROCOF_{060}$: df over time from 20 % to 80 % t_{nadir} (t_{zenith});

- $ROCOF_{100}$: df over t_{nadir} (t_{zenith}).

High inertia systems have slower frequency dynamics with high damping resulting in low frequency transients. With high penetration of traditional wind turbines and photovoltaics, the available inertia decreases. Therefore, the impact of generation or load imbalance on system stability rises. For the rotating masses, the first seconds, i.e. first swing frequency, is the most critical time. Here, the rate of change of frequency (ROCOF) is the highest. After a few seconds, the primary response of the synchronous generators is activated, and the frequency is stabilized.

Primary and secondary frequency responses are well known and used in the operation of power systems shown in Figure 16. The major issue is the inertial response shown in Figure 17, i.e. the time until the primary frequency reserve comes in full operation. It is worth noting that the inertial response is not completely equal to the fast frequency response, because the frequency measurement has a certain time delay, and the delay time is different for different systems. Depending on the different grid codes this time can be a few seconds. The main challenges for fast frequency response are:

a) increasing the f_{nadir} to avoid load shedding (under-frequency) and decreasing the f_{zenith} to avoid generation disconnection (over-frequency);

b) reducing the ROCOF to avoid the tripping of generating units for the application as a fast frequency response, i.e. a bridge between outage and primary frequency response.
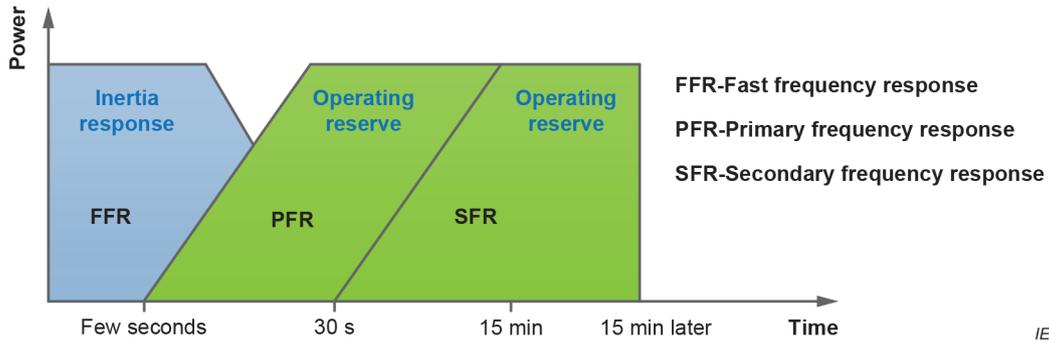
Figure 16 – Example of operation regions of different frequency response types
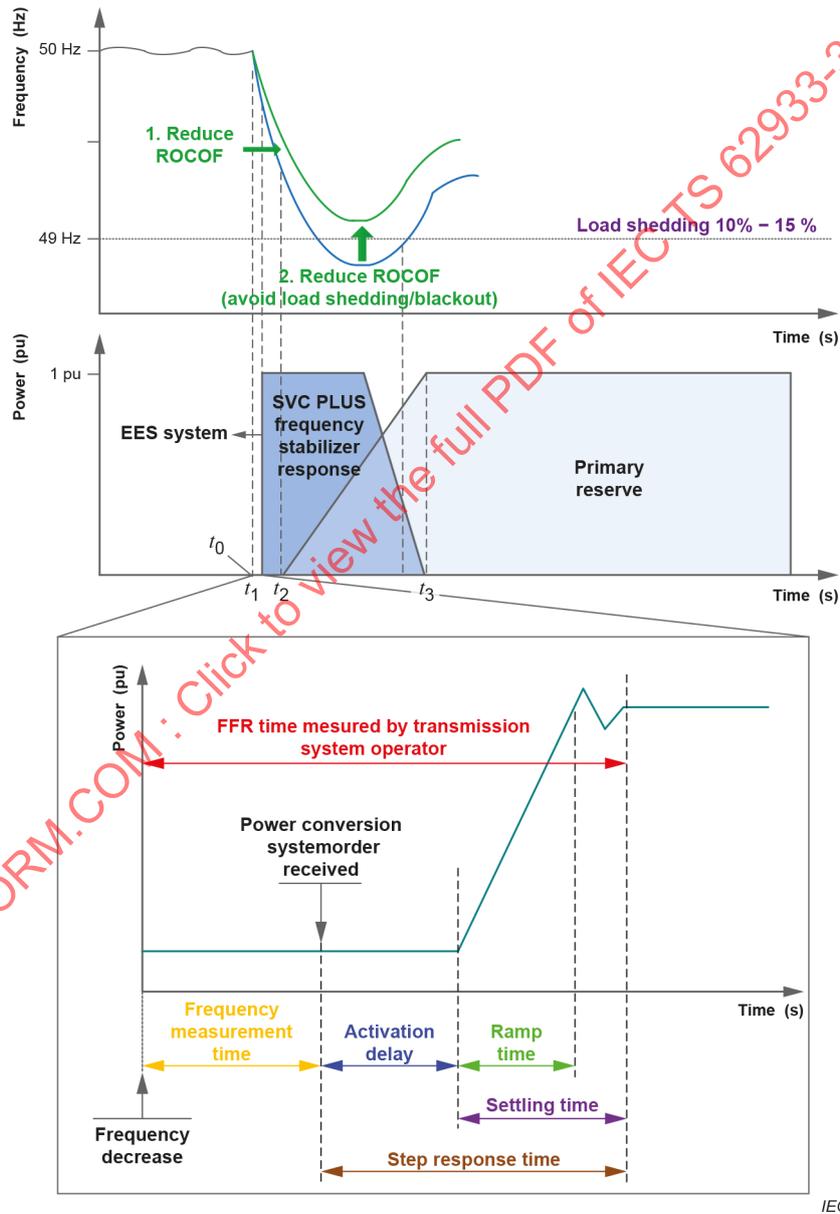
Figure 17 – Example of frequency and EES system output power curve with time

The main parameters describing the duration of fast frequency control are:

- t_0: the time when the frequency starts to fall;

- t_1: includes the frequency measurement time and step response time;

- t_2: the time when primary frequency regulation starts;

- t_3: the time when fast frequency control ends.

The fast frequency control could be accomplished both by considering the f value for calculating $P(f)$ (in a faster way than primary frequency response), and/or considering the ROCOF for calculating $P(ROCOF)$.

5.2.2   Conditions and requirements for connection to the grid

Subclause 4.2 is applicable.

5.2.3   Design of the EES systems

5.2.3.1   Structure of the EES systems

The EES systems structure and components defined in 4.3.2 are also applied to the fast frequency control applications. In addition to these, there exist additional considerations. The EES system for fast frequency control applications should be installed in conjunction with renewable energy sources such as PV, wind turbine, etc. A typical configuration of EES systems in conjunction with renewable energy sources is shown in Figure 18.

Figure 18 – Example of the system structure of EES systems for fast frequency control application in conjunction with renewable energy sources

5.2.3.2   Subsystem specifications

Subclause 4.3.3 is applicable.

5.2.3.3   Grid integration of the EES systems

Subclause 4.3.4 is applicable.

5.2.3.4   Operation and control

Fast frequency control is a combination of control algorithms, EES system, and power electronics that emulates the inertia of a conventional power system with a specified inertia constant. Virtual inertia control is a common method of the EES system for fast frequency control. Once the ROCOF exceeds the dead band, the EES system starts to simulate the virtual inertia response of the traditional generator according to the frequency change rate, so as to slow down the frequency change rate during sudden system failure and reduce the amplitude of the transient frequency difference, as shown in Figure 19, where $\Delta\omega_J$ is the angular frequency deviation, $\Delta\omega_{J0}$ is the angular frequency deviation in steady state, T_J is the time constant of inertia and K_D is the damping coefficient.
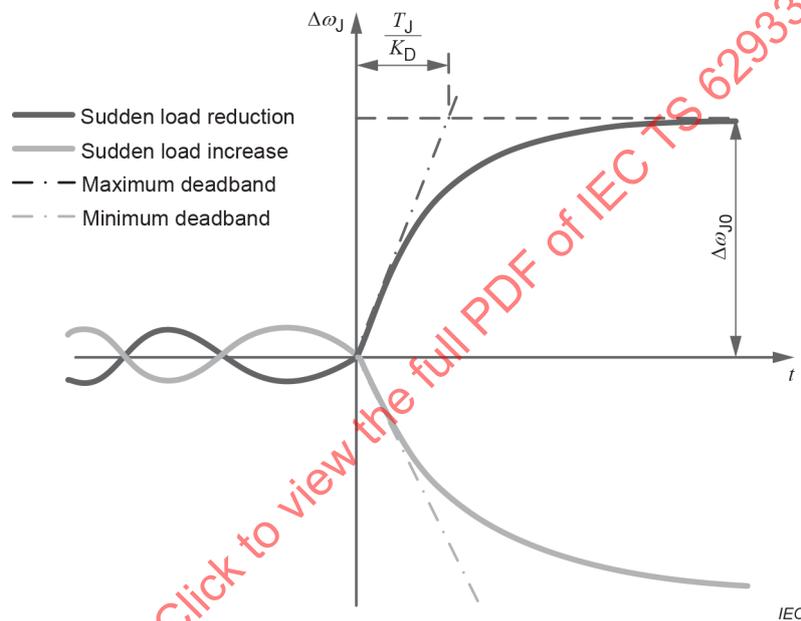
Figure 19 – Frequency deviation curve

The calculation formula for the virtual inertial control of the EES system is as follows:

$$\Delta P_{IR}(t) = \begin{cases} K_{IR}\left(df_t / dt\right) & df_t / dt \le R_{min} \text{ or } df_t / dt \ge R_{max} \\ 0 & R_{min} < df_t / dt < R_{max} \end{cases}$$

where

$\Delta P_{IR}(t)$ is the active power output at time t;

K_{IR} is the virtual inertia coefficient;

df_t/dt is the ROCOF at time t;

R_{min} is the negative boundary of the dead band of the frequency change rate;

R_{max} is the positive boundary of the dead band of the frequency change rate.

Another method of control is to implement a curve similar to the power-frequency droop curve, except with the rate of change of the frequency on the x-axis instead of the frequency.

Some other control methods are:

a) active power injection in proportion to measured frequency deviation (proportional response);

b) injection of constant amount of active power once frequency reaches a preset trigger point (step response);

c) active power injection in proportion to calculated ROCOF (derivative response);

d) injection of constant amount of active power once a preset ROCOF is reached (step response);

e) controlled load reduction in proportion to measured frequency deviation or ROCOF (proportional or derivative response);

f) controlled reduction of constant amount of load on a preset frequency or once ROCOF is reached (step response).

5.2.3.5 Communication interface

Subclause 4.3.8 is applicable.

5.2.4 Sizing and resulting parameters of the EES systems

5.2.4.1 Sizing

a) Sizing process of the EES system

The general sizing process of the EES system for fast frequency control is shown in Figure 20.
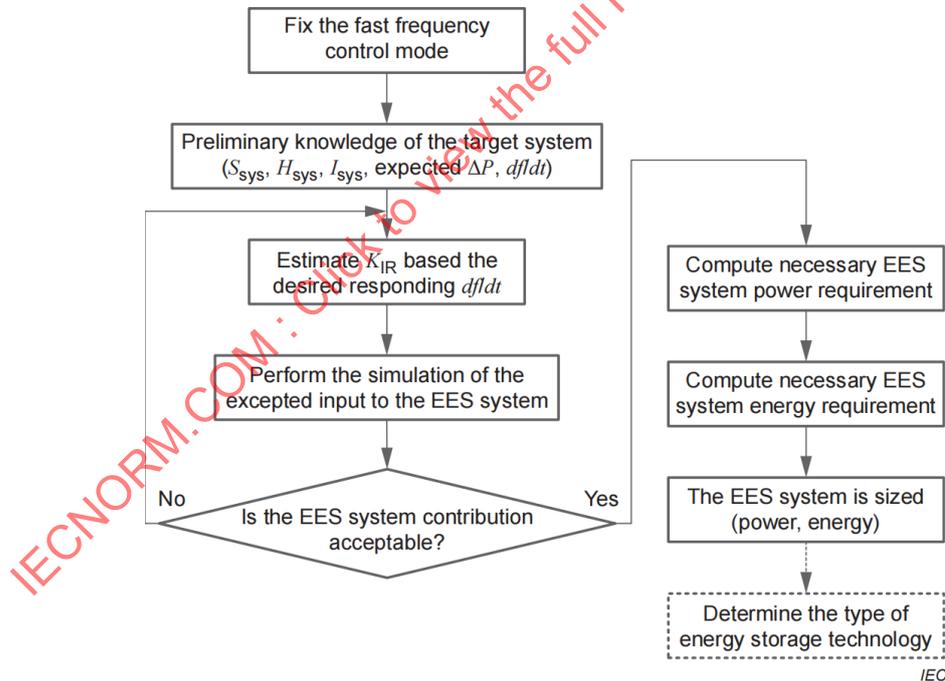
Figure 20 – Example of EES system sizing process for fast frequency control

In Figure 20, the method uses the preliminary knowledge of the target system, namely system size (S_{sys}), system inertia (H_{sys}), and power/frequency characteristic (I_{sys}). The user shall decide the target power (ΔP) unbalance for which the EES system is going to be sized.

b) Requirements for sizing

The planning input for an EES system shall include the following:

- power system characteristics at primary POC;

- target functionality: frequency control;
- determination of the required $P_{\text{EES system}}$ or $Q_{\text{EES system}}$ and appropriate duration $t_{\text{EES system}}$ of the EES system as well as requirements for system control.

5.2.4.2   Characteristics and restrictions of the EES systems

Subclause 4.4.3 is applicable.

5.2.5   Service life of the EES systems

5.2.5.1   Installation

Subclause 4.5.2 is applicable.

5.2.5.2   Performance assessment

Subclause 4.5.3 is applicable.

5.2.5.3   Operation and control

The fast frequency control of the EES system can control the dynamic process of the frequency changes. When the load changes suddenly, the corresponding inertia link ensures that the EES system injects active power into the grid continuously and rapidly, making the frequency slowly transition to the new steady state value. The operation and control process are shown in Figure 21.
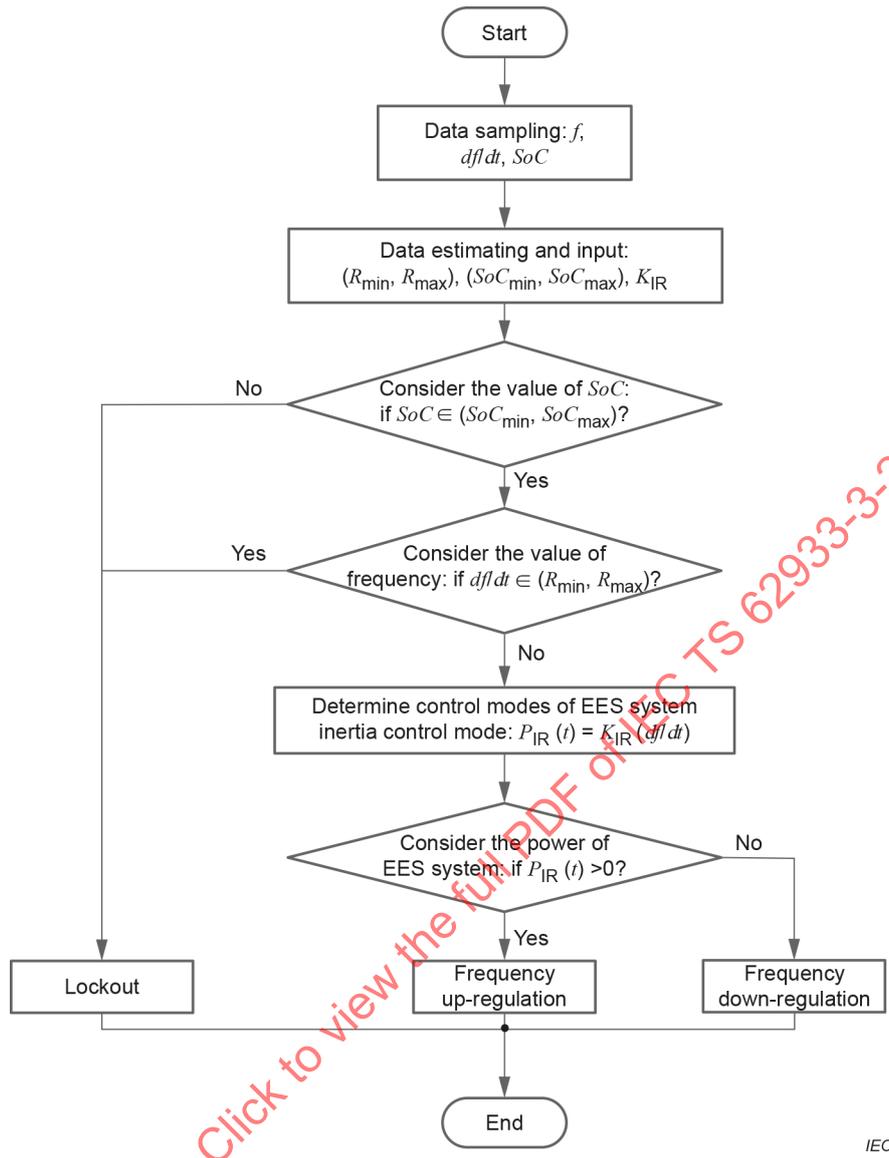
Figure 21 – Example of control strategy of the EES system participating in fast frequency control

NOTE   The idling SOC of the EES system can be set to 50 %, allowing the EES system to participate in both frequency up-regulation and down-regulation services.

5.2.5.4   Monitoring

Subclause 5.1.5.4 is applicable.

6   Grid voltage support ($Q(U)$), volt/var support

6.1   Applications of the EES systems

6.1.1   Functional purpose of the EES systems

A requirement for an electrical system operator is to maintain voltage within the specified limits. Voltage support resources are needed to offset reactive power effects, so that the transmission system can be operated in a stable manner. In some specific cases, active power is also needed for voltage support/regulation.

Normally, some sources are used to generate reactive power. These general sources could be displaced by EES systems taking a central or distributed control approach. The PCS of EES systems used for voltage support should be capable of operating at a variable power factor, to sink and source reactive power or volt-ampere reactive power. This capability is available in all PCSs used in today's storage systems. Grid voltage support is usually used as an auxiliary service, not as a separate application scenario. Grid voltage support plans can vary and include reactive and real power controls to achieve the desired voltage control.

6.1.2   Application related requirements

The selected equipment shall have the following characteristics, to properly deliver the functionality for the application.

a) Voltage deviation

The voltage deviation is the ratio of the difference between the local measured voltage at POC and the rated voltage.

$$\Delta V\% = \frac{V_{POC} - V_R}{V_R} \times 100\%$$

where

$\Delta V\%$ is the percentage of voltage deviation;

V_{POC} is the local measured voltage at the POC;

V_R is the rated voltage.

b) Reactive power response time

The reactive power response time is the response time of the EES system in responding to a reactive power command signal. The response time takes a stand-by EES system to sink or source reactive power to 98 % of rated reactive power from an initial reactive power measurement.

c) Reactive power ramp rate

The reactive power ramp rate is the rate of change of the reactive power sunk or sourced by an EES system, which is expressed as a percentage change in the rated reactive power over time (percent per second).

6.2   Conditions and requirements for connection to the grid

Subclause 4.2 is applicable.

6.3   Design of the EES systems

6.3.1   Structure of the EES systems

The EES system structure and components defined in 4.3.2 are also applied to the grid voltage support application. There exist also additional considerations. An EES system for grid voltage support applications should be installed in conjunction with the grid in order to improve the effectiveness of the grid voltage support application. An example of the system structure of the EES system for grid voltage support is shown in Figure 22. Among other, the voltage detection system is responsible for detecting the voltage, operation and control system, for analysing the voltage information and then dispatching the voltage regulation signal to the management subsystem.
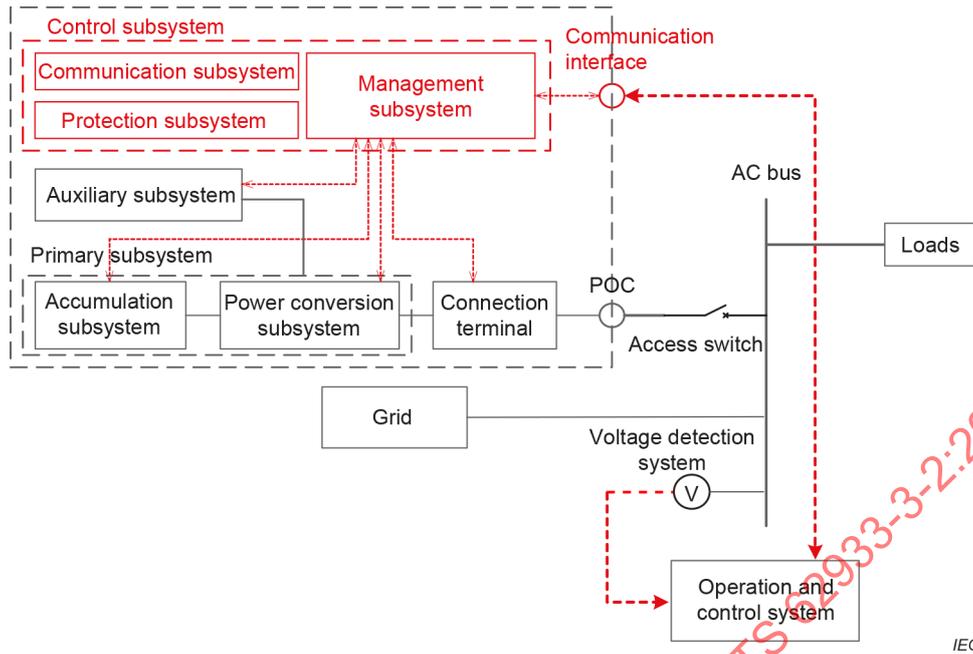
Figure 22 – Example of the system structure of the EES system for grid voltage support

6.3.2 Subsystem specifications

Subclause 4.3.3 is applicable.

6.3.3 Grid integration of the EES systems

Subclause 4.3.4 is applicable.

6.3.4 Operation and control

The application of the EES system to support the grid voltage is done by sinking or sourcing reactive power to the grid. As shown in Figure 23, there are four points, labelled V_1 through V_4. The piece-wise linear curve will include for each point a voltage, given in percentage of the reference voltage V_{Ref}, and a desired reactive power level, given in percentage of available reactive power, see description below.

By definition, the desired reactive power level is assumed to remain constant for voltages below V_1 (e.g. at the Q_1 level) and above the highest voltage point, at Q_4. As shown, the first point in the voltage support configuration is the lowest voltage point and the last is the highest voltage.
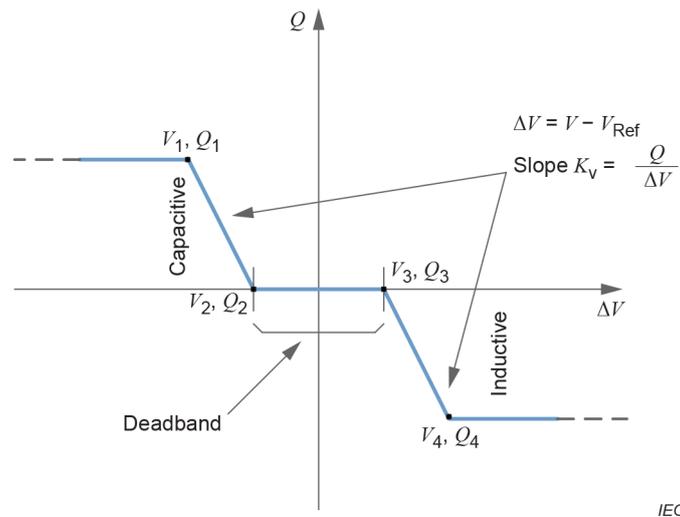
Figure 23 – Example of reactive voltage support schematic diagram

NOTE   In the figure, the dead band can be configurable and by default is equal to zero ($V_2 = V_3$).

The EES system used for voltage support should be capable of operating at a variable power factor, to sink and source reactive power.

6.3.5   Communication interface

Subclause 4.3.8 is applicable.

6.4   Sizing and resulting parameters of the EES systems

6.4.1   Sizing

a) Sizing process of the EES system

   The general sizing process of the EES system for the voltage support is shown in Figure 24.
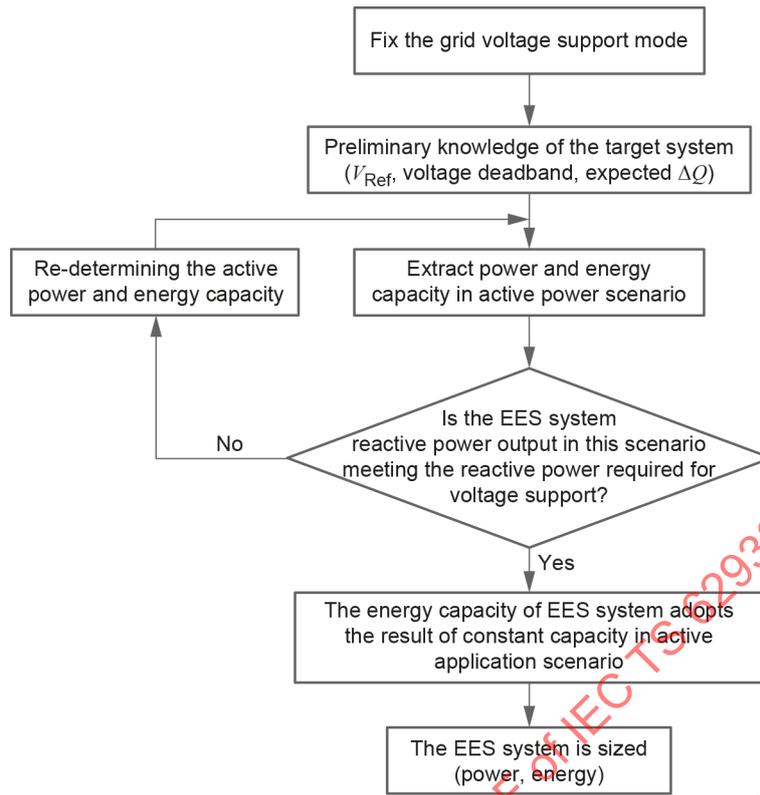
Figure 24 – Example of EES system sizing process for voltage support

b) Requirements for sizing

When performing the sizing process of the EES system, the following requirements shall be met:

- The power supply and storage capacity of the power station shall be considered when determining the sizing of the EES system.

- Different control strategies shall be considered when determining the sizing of the EES system.

- The accumulation subsystem life, charge-discharge characteristics, optimal charge-discharge interval and economy shall be considered when determining the sizing of the EES system.

- The energy storage capacity shall be comprehensively determined in accordance with the historical characteristics of the grid voltage and the seasonal difference of the load profile.

6.4.2 Characteristics and restrictions of the EES systems

Subclause 4.4.3 is applicable.

6.5 Service life of the EES systems

6.5.1 Installation

Subclause 4.5.2 is applicable.

6.5.2 Performance assessment

Subclause 4.5.3 is applicable.

6.5.3   Operation and control

The control objective of this mode is the voltage of the power system. When the power system cannot provide a stable voltage, the reactive power control of the EES system is started to balance the reactive power, which in turn regulates the voltage of the power system indirectly and benefits the voltage recovery to an allowable range. When the power system voltage returns to a reasonable range, the EES system will automatically exit the voltage adjustment function. The grid voltage support is also related to the active power and SOC.

6.5.4   Monitoring

The following shall be monitored:

- equipment malfunction alarm;

- equipment status signals (e.g. state of breakers and switches: On/Off);

- operating temperatures;

- response curve parameters for reactive power output versus voltage.

The following parameters are required to determine whether the EES system can functionally perform grid voltage regulation based on the system voltage:

– Voltage (U): This represents the voltage during EES system operation.

– Active power (P): This represents the active power delivered during EES system charging or discharging, excluding the power required to satisfy auxiliary loads.

– Reactive power (Q): This represents the reactive power delivered during EES system charging or discharging, excluding the reactive power associated with auxiliary loads.

– Reactive current (I_r): Reactive current is under direct control of the PCS. These current limits are the reactive counterpart of the current limits in the active power path and are designed to give priority to active over reactive power orders.

7   Voltage sag mitigation ($P(U)$)

7.1   Applications of the EES systems

7.1.1   Functional purpose of the EES systems

The voltage sag event is defined as problems of power quality when the root-mean-square value of the AC voltage drops under 0,9 per unit and above 0,01 per unit, lasting from 0,5 cycles to 1 min. The provision of active power to compensate voltage sag is typical for the EES system connected to distribution networks. Figure 25 shows an example of voltage sag in IEC 61000-4-11 and the following applies.

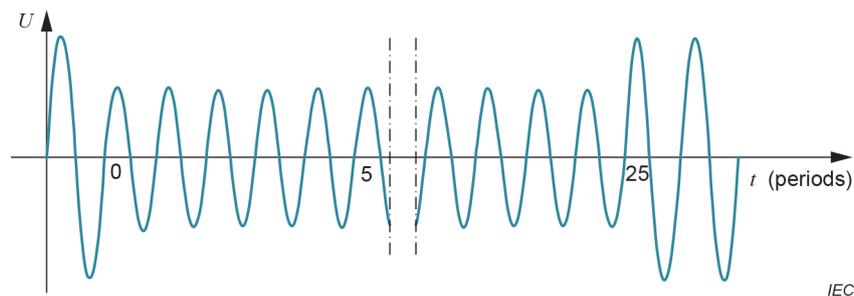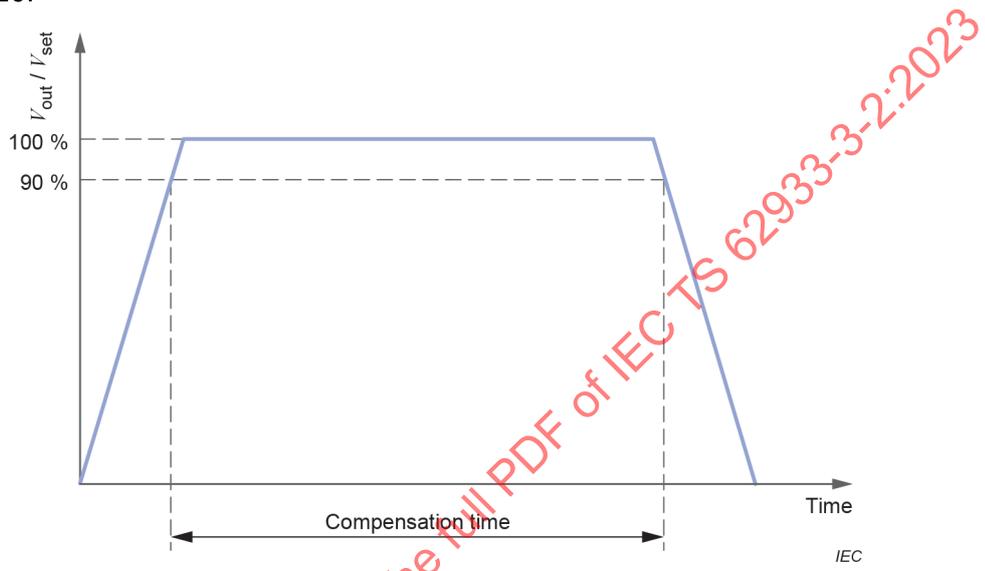

Figure 25 – Example of voltage sag

It is widely known that voltage sag can have a strong impact on high reliability power supply customers. A lot of EES systems can mitigate voltage sag by injection of active/reactive power for up to 1 min.

The application of the EES system to solve voltage sag does not require the EES system to provide customers with enough energy. Since voltage sag involves discharge, the starting remaining energy can be up to $SoC_{reserve\_max}$ and the lower limit is $SoC_{reserve\_min}$ (to ensure that the EES system can provide peak power at the lower limit of the remaining energy range).

7.1.2   Application related requirements

a) Compensation time

The compensation time is the duration from the output voltage value (V_{out}) rising to 90 % of the set voltage value (V_{set}) to the output voltage falling to 90 % of the set value, as shown in Figure 26.

**Figure 26 – Example of compensation time of the
EES system for voltage sag mitigation**

b) Rated compensation power

The rated compensation power is the product of the EES system's rated compensation voltage and rated current.

c) Rated compensation time

The rated compensation time is the time required for the EES system to operate at the rated compensation power, which shall be not less than 1 min.

d) Regulation time

When the grid voltage drops to 90 % of the nominal voltage value (V_n), the regulation time is shown in Figure 27, which indicates the time taken for the EES system to contribute to finally compensate the load voltage value (V_{load}) to 90 % of the nominal voltage of the grid.
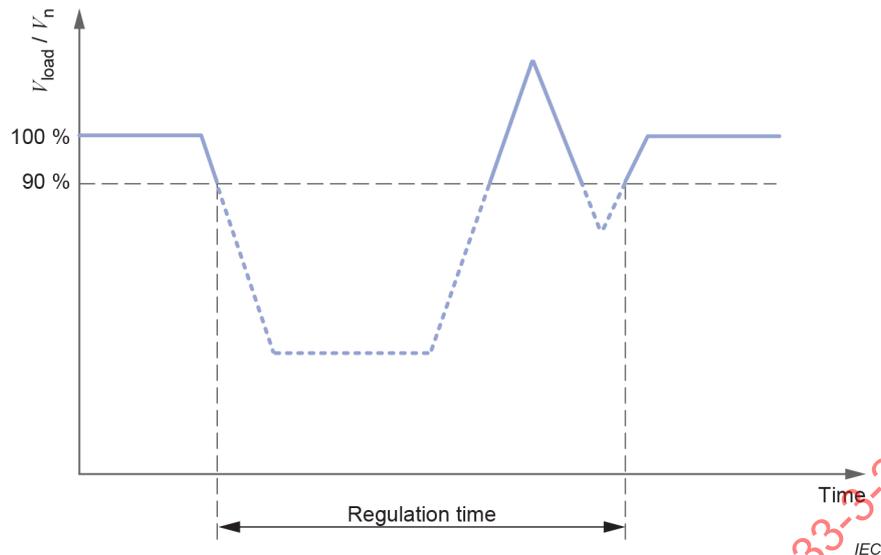
**Figure 27 – Example of regulation time of the EES
system for voltage sag mitigation**

e) Energy requirements

Subclause 4.1.2.4 is applicable.

f) Efficiency requirements

Subclause 4.1.2.5 is applicable.

g) Response time and ramp rate requirements

Subclause 4.1.2.6 is applicable.

7.2   Conditions and requirements for connection to the grid

Subclause 4.2 is applicable.

7.3   Design of the EES systems

7.3.1   Structure of the EES systems

The EES system structure and components defined in 4.3.2 are also applied to the voltage sag mitigation application. In addition to them, there exist additional considerations. An EES system for voltage sag mitigation application should be installed in conjunction with important loads in order to improve the effectiveness of voltage sag mitigation application. An example of the system structure of the EES system for voltage sag mitigation is shown in Figure 28.
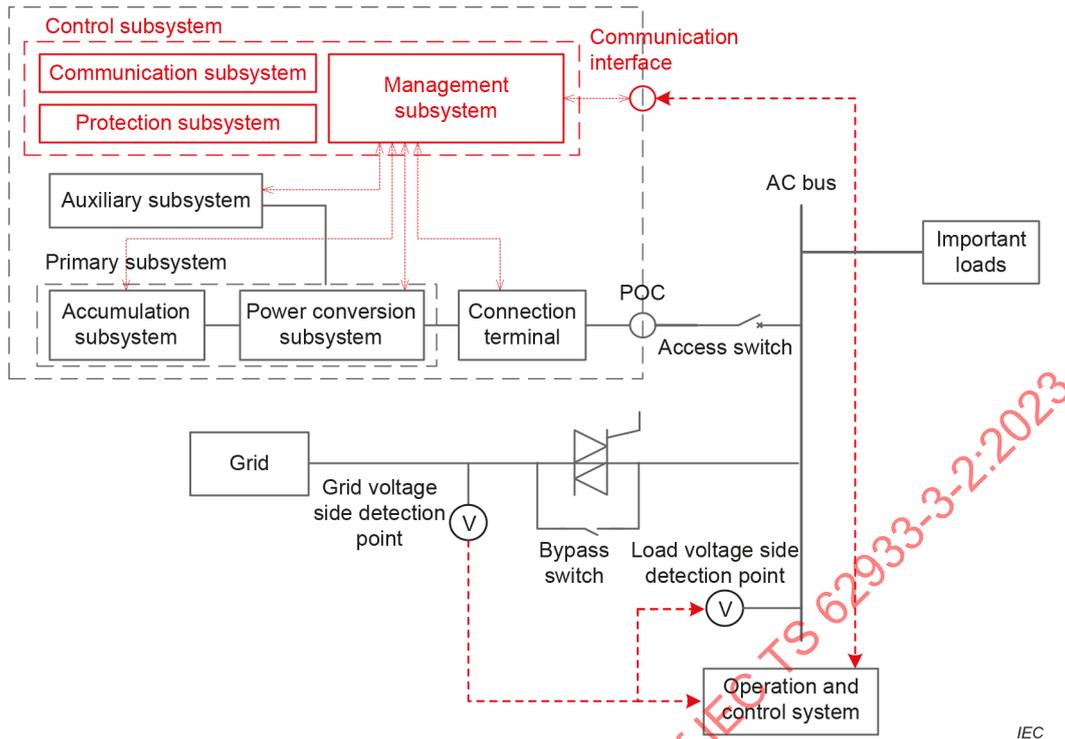
Figure 28 – Example of the system structure of the EES system for voltage sag mitigation

The grid integration of the EES system for voltage sag mitigation is mainly composed of the power grid, voltage detection system, EES system, switch, important loads, and operation and control system. When the grid voltage is normal, the grid supplies power to important loads and the EES system. The grid side and load side voltage detection systems detect the voltage in real time to determine whether voltage sag occurs. When it occurs, the EES system can mitigate voltage sags by injecting real power for up to 1 min. The static switch isolates the important load from the grid quickly. The bypass switch can be composed of mechanical switches, such as circuit breakers and contactors for device protection and bypass. The operation and control system is the monitoring and control centre, which is responsible for receiving the voltage sag signal, monitoring the real status of EES system, and controlling the EES system to discharge.

7.3.2 Subsystem specifications

Subclause 4.3.3 is applicable.

7.3.3 Grid integration of the EES systems

Subclause 4.3.4 is applicable.

7.3.4 Operation and control

An example of control strategy for the voltage sag mitigation application is shown in Figure 29. When the grid voltage is in normal condition, the static switch is in the closed state, and the grid supplies power to important loads and the EES system. The voltage detection system monitors the grid voltage and the important load voltage in real time. When the RMS value of the grid voltage drops to 90 % of the rated value, the static switch is turned off, and the EES system supplies power to the important load. After the grid voltage returns to the normal value, the static switch is turned on, the EES system stops discharging, and the grid is restored to the original stable operating state.
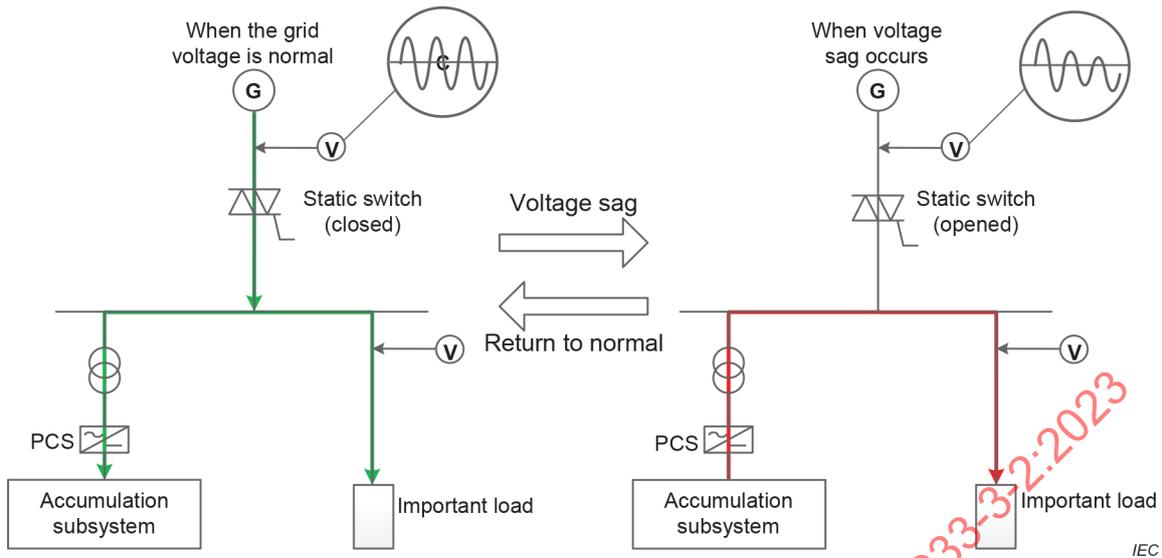
Figure 29 – Example of control strategy for the voltage sag mitigation application

7.3.5 Communication interface

Subclause 4.3.8 is applicable.

7.4 Sizing and resulting parameters of the EES systems

7.4.1 Sizing

a) Sizing process of the EES system

The general sizing process of the EES system for the voltage sag mitigation is shown in Figure 30.
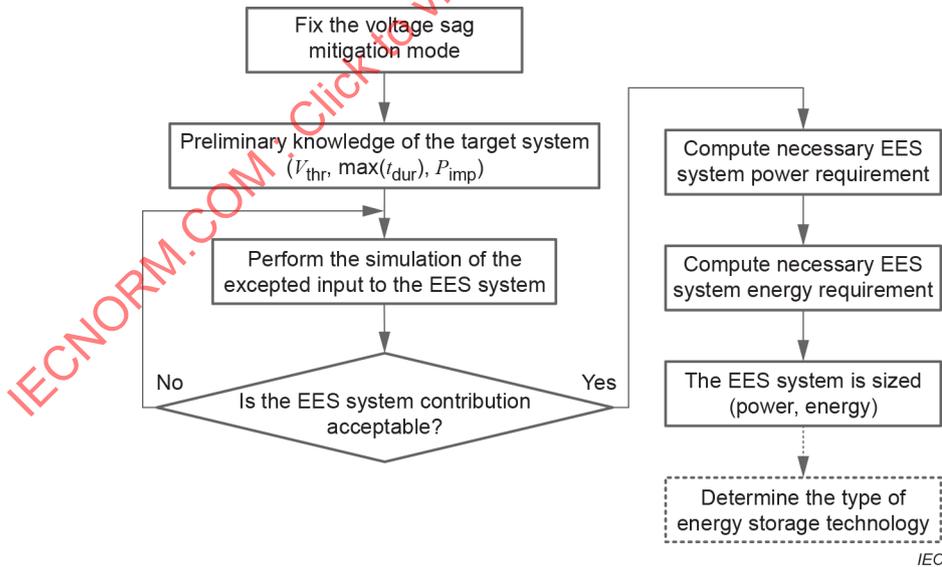
Figure 30 – Example of EES system sizing process for voltage sag mitigation

NOTE   In the figure, V_{thr} is the voltage threshold used to determine the start and end of the voltage sag. $\max(t_{dur})$ is the maximum duration of the voltage sag time to reach V_{thr}, and P_{imp} is the important load power.

b) Requirements for sizing

The following requirements shall be taken into account in order to size the capacity of the EES system for voltage sag mitigation:

- The dynamic voltage support performance of the PCS shall be considered.
- Research of historical voltage sag curves shall be used for sizing:
  - sag time [s], sag depth [%], and grid recovery time [s or min]
- Research of immunity and inrush power in the important load:
  - load immunity [%/s], load inrush power [kW]
- Decision about the specification and sizing of the system:

$$T_s = T_d + T_{off} + T_{pcs} < T_{imm}$$

$$P_s > P_{inr}$$

$$T_c > T_{his} + T_{con} + T_{on} > T_{rec}$$

$$E > P_{rate} \times T_c$$

$$T_{int} = T_{next} < T_{his,int}$$

where

T_s is the system switching time;

T_d is the sag detection time;

T_{off} is the main switch off time;

T_{pcs} is the PCS activation or mode change (from charge-discharge to isolation-discharge) time;

T_{imm} is the immunity time of important load;

P_s is the system power at very short duration;

P_{inr} is the inrush power of important load;

T_c is the system compensation time;

T_{his} is the historical sag time;

T_{con} is the grid voltage confirmation time;

T_{on} is the main switch on time;

T_{rec} is the grid recovery time (depending on the utility);

E is the system storage capacity;

P_{rate} is the important load rated power;

T_{int} is the system interval time;

T_{next} is the system capability from sag to next sag;

$T_{his,int}$ is the historical sag interval.

7.4.2 Characteristics and restrictions of the EES systems

Subclause 4.4.3 is applicable.

7.5 Service life of the EES systems

7.5.1 Installation

Subclause 4.5.2 is applicable.

7.5.2 Performance assessment

Subclause 4.5.3 is applicable.

7.5.3 Operation and control

The control process of the EES system when the voltage sag occurs in the power grid is as follows:

- In normal working conditions, the static switch is closed, and the load is powered by the grid.

- The operation and control system samples the grid voltage in real time.

- The operation and control system can detect the fault, and send a command to the static switch and PCS. The static switch is quickly disconnected after receiving the command, and the load is disconnected from the grid.

After receiving the command, the PCS establishes the rated output voltage and starts to supply power to ensure the important load is powered by the EES system after the static switch is disconnected. The voltage sag mitigation application requires the cooperation of various components in the system.

7.5.4 Monitoring

- The monitoring system shall automatically complete the voltage sag detection, start compensation, stop compensation and other operations to ensure that the load side voltage is within the allowable range.

- The monitoring system shall have a human-machine interface for local operation, and shall have a communication interface for remote detection and control.

- The monitoring system shall at least perform the following operations on the local monitoring interface: switch separation, device start and stop, and signal reset.

- The monitoring system shall automatically complete the outage operation except the isolation switch.

- The monitoring system shall display the required information to allow the operation and maintenance personnel to observe the operation of the equipment and locate the cause of the failure.

The data of the switching devices to be monitored include:

– the switching status of the static switch and bypass switch at the grid side;

– the switching status of the access switch at the POC.

The monitoring system shall have at least the following features:

a) operating status display;

b) main system diagram display (including position information of each switch);

c) analogy display (system voltage, load voltage, device current, DC voltage);

d) event recording and display query function;

e) recording function and display: when the system voltage is abnormal or the device is faulty, it can automatically record the important data (voltage, current, switch position, etc.) before and after the event. The recording time is greater than 2 min and the sampling frequency is not less than 5 kHz;

f) cooling system operating status display.

8   Renewable energy sources integration related applications

8.1   Renewable energy sources (power) smoothing

8.1.1   Applications of the EES systems

8.1.1.1   Functional purpose of the EES systems

The EES system can smooth the renewable energy sources (power) fluctuation by absorbing or releasing power at the appropriate time. The time is determined by a control system resulting in a less variable composite power signal at the feeder and/or transmission level. The key of this application is to help meet the ramp rate requirements. The time duration of smoothing is determined by the control system, usually in a period of seconds to a few minutes.

8.1.1.2   Application related requirements

The selected equipment shall have the following characteristics, to properly deliver the functionality for the application.

a) Power smoothing effectiveness of renewable energy

The following metrics are developed to characterize the degree to which renewable energy sources (power) are effectively smoothed by the EES system:

1) Reduction in standard deviation of power (RSDP)

   The metric for quantifying the impact that the EES system device has on smoothing the renewable energy power output is the so-called reduction in standard deviation of power (RSDP). The reduction of the standard deviation η_{RSDP} between the unsmoothed power and the smooth power describes the degree to which the power can deviate from its mean value, so as to show the smoothness of the EES system:

$$\eta_{RSDP} = 100 \times \left(1 - \frac{\hat{\sigma}_{smooth}}{\hat{\sigma}_{unsmooth}} \right)$$

   where

   $\hat{\sigma}_{smooth}$ is the standard deviation of the smoothed renewable energy residue;

   $\hat{\sigma}_{unsmooth}$ is the standard deviation of the unsmoothed renewable energy residue.

2) Reduction in standard deviation of ramp rate (RSDR)

   The reduction in ramp rate η_{RSDR} represents the EES system's ability to dampen the rate at which power fluctuations occur.

$$\eta_{RSDR} = 100 \times \left(1 - \frac{\hat{\zeta}_{smooth}}{\hat{\zeta}_{unsmooth}} \right)$$

   where

   $\hat{\zeta}_{smooth}$ is the standard deviation of the smoothed renewable energy ramp rate;

   $\hat{\zeta}_{unsmooth}$ is the standard deviation of the unsmoothed renewable energy ramp rate.

3) Max-min reduction

Max-min reduction η_{swing} represents an intuitive measurement of the EES system's usefulness by quantifying how well the day's largest power swing is diminished. The significance of this metric is to determine how well the maximum power swing $P_{\text{swing,max}}$ of the day is mitigated. A high-performing smoothing will reduce these maximum power swings well. The max-min reduction can be defined as the reduction in:

$$\hat{R}(n) = X(n) - \frac{1}{N+1} \sum_{n=-\frac{N}{2}}^{\frac{N}{2}} X(n)$$

$$P_{\text{swing,max}} = \max \left| \hat{R}(n) \right|$$

$$\eta_{\text{swing}} = 100 \times \left(1 - \frac{\hat{R}_{\text{smooth}}(m)}{P_{\text{swing,max}}} \right)$$

where

N is the number of samples per minute of renewable energy output;

$X(n)$ is the renewable energy power signal;

$\hat{R}(n)$ is the residue of $X(n)$;

m is the linear index of $P_{\text{swing,max}}$.

By looking at the maximum of the above described residue function $\hat{R}(n)$ of the unsmoothed power data set, the magnitude of the largest power swing of that particular day can be determined.

b) Energy requirements

Subclause 4.1.2.4 is applicable.

c) Efficiency requirements

Subclause 4.1.2.5 is applicable.

d) Response time and ramp rate requirements

Subclause 4.1.2.6 is applicable.

## 8.1.2 Conditions and requirements for connection to the grid

Subclause 4.2 is applicable.

8.1.3 Design of the EES systems

8.1.3.1 Structure of the EES systems

The EES system structure and components defined in 4.3.2 are also applied to the renewable energy sources (power) smoothing application. In addition, there exist additional considerations. The EES system should be installed in conjunction with renewable energy sources such as PV, wind turbine, etc. An example of the system structure of the EES system connected with renewable energy sources is shown in Figure 31. The EES system and renewable energy sources can be linked to the operation and control system through communication interfaces.
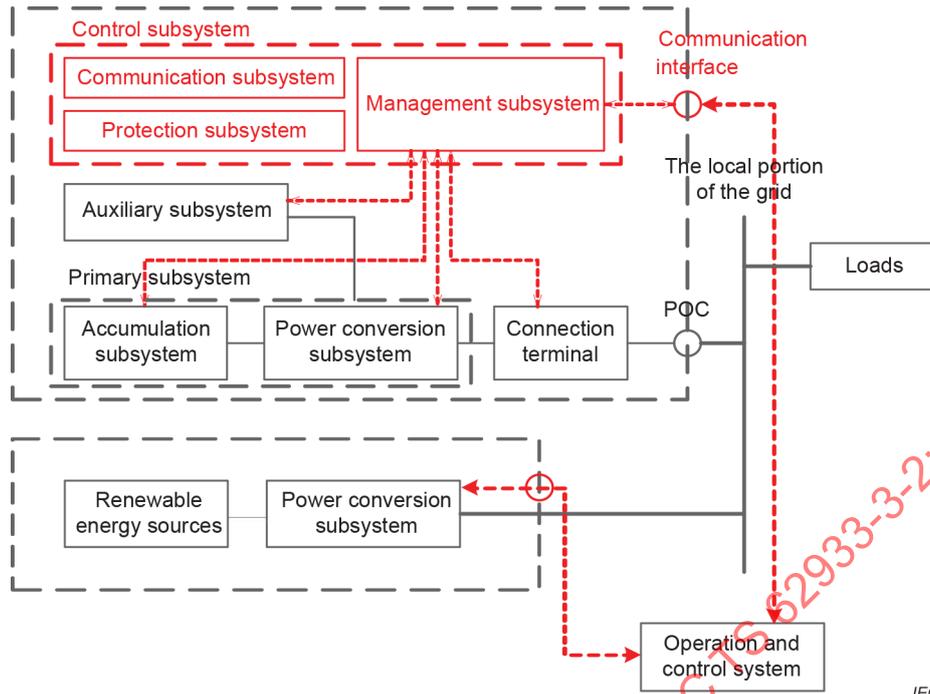
Figure 31 – Example of the system structure of the EES system connected with renewable energy sources

8.1.3.2 Subsystem specifications

Subclause 4.3.3 is applicable.

8.1.3.3 Grid integration of the EES systems

Subclause 4.3.4 is applicable.

8.1.3.4 Operation and control

In accordance with the operation requirements in the renewable energy sources (power) smoothing, the automatic smoothing program in the control subsystem controls the EES system to handle the renewable energy sources in accordance with the set smooth range, so as to realize the smooth fluctuation within the specified range. An example of control strategy for the renewable energy sources (power) smoothing is shown in Figure 32.
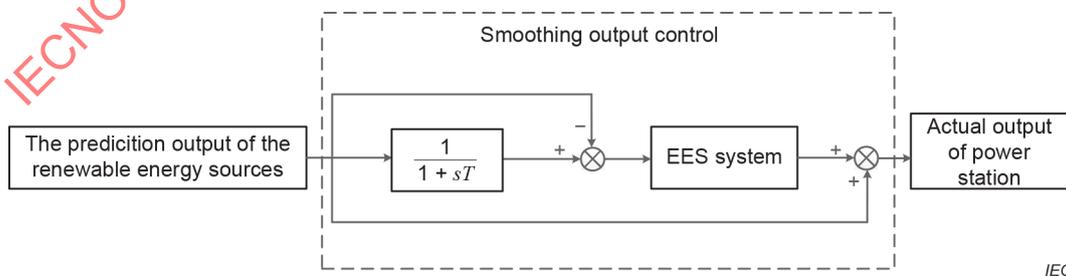
Figure 32 – Example of control strategy for the renewable energy sources (power) smoothing application

8.1.3.5 Communication interface

Subclause 4.3.8 is applicable.

8.1.4 Sizing and resulting parameters of the EES systems
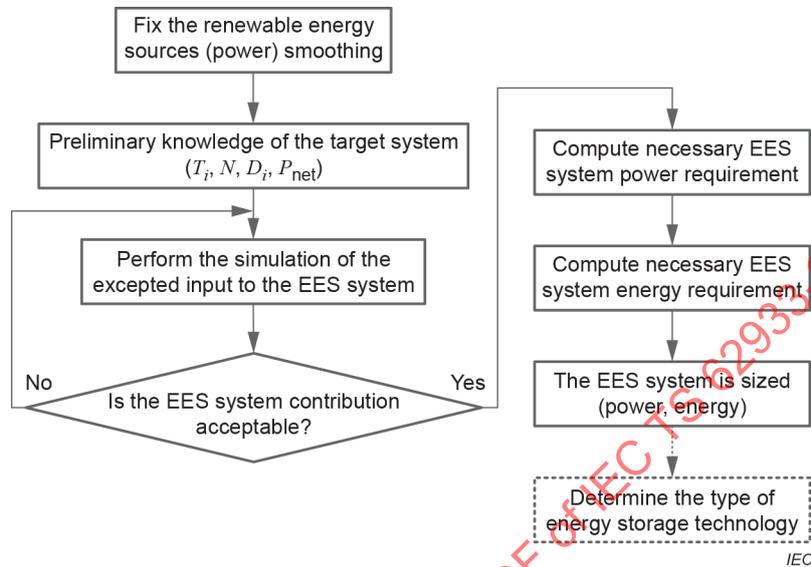
8.1.4.1 Sizing

a) Sizing process of the EES system

The general sizing process of the EES system for the renewable energy sources (power) smoothing is shown in Figure 33.

Figure 33 – Example of the EES system sizing process for renewable energy sources (power) smoothing

In Figure 33, T_i is the set time scale, N is the number of samples per minute of renewable energy output, and D_i is the allowable output change limit under time scale T_i.

There are three different kinds of mathematical expressions for the output change constraints on the T_i time scale:

– The instantaneous power fluctuation limit: for any two moments t, $t - T_i$ with an interval of T_i, the instantaneous power $P_\text{net}(t)$, $P_\text{net}(t - N\,T_i)$ shall satisfy the fluctuation limit constraint described in the following formula.

$$-D_i \le P_\text{net}(t) - P_\text{net}(m) \le D_j \qquad \left(-NT \le m < 0\right)$$

– The average power fluctuation limit: for two adjacent periods $t - T_i \sim t$, $t \sim t + T_i$ separated by T, the difference of the average power between the two shall be within the fluctuation limit D_i.

$$-D_i \le \frac{1}{NT_i} \sum_{m=t}^{t+NT_i-1} \left(P_\text{net}(m) - P_\text{net}(m - NT_i)\right) \le D_i$$

– The limit power fluctuation limit: for the period $t \sim t + T_i$ with a time span of T_i, the difference between the maximum power and the minimum power in this period shall be less than the output change limit D_i under this time scale.

$$\max_{m=t,t+1,\cdots,t+NT_i} P_\text{net}(m) - \min_{m=t,t+1,\cdots,t+NT_i} P_\text{net}(m) \le D_i$$

b) Requirements for sizing

When performing the sizing process of the EES system, the following requirements shall be met:

- The power supply and storage capacity of the power station shall be considered when determining the sizing of the EES system.

- The grid-connected requirements of renewable energy sources shall be considered.

- Different control strategies shall be considered when determining the sizing of the EES system.

- The accumulation subsystem life, charge-discharge characteristics, optimal charge-discharge interval and economy shall be considered when determining the sizing of EES system.

- The EES system capacity shall be comprehensively determined according to the historical output characteristics of the renewable energy sources and the seasonal difference of the output power.

8.1.4.2 Characteristics and restrictions of the EES systems

Subclause 4.4.3 is applicable.

8.1.5 Service life of the EES systems
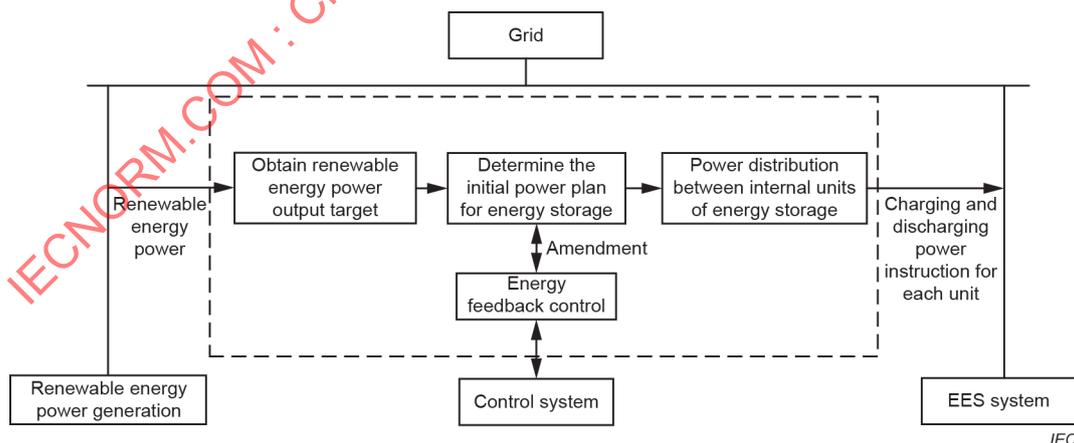
8.1.5.1 Installation

Subclause 4.5.2 is applicable.

8.1.5.2 Performance assessment

Subclause 4.5.3 is applicable.

8.1.5.3 Operation and control

The basic procedures of the EES system in the renewable energy sources (power) smoothing are shown in Figure 34.

Figure 34 – Example of renewable energy sources (power) smoothing basic procedures
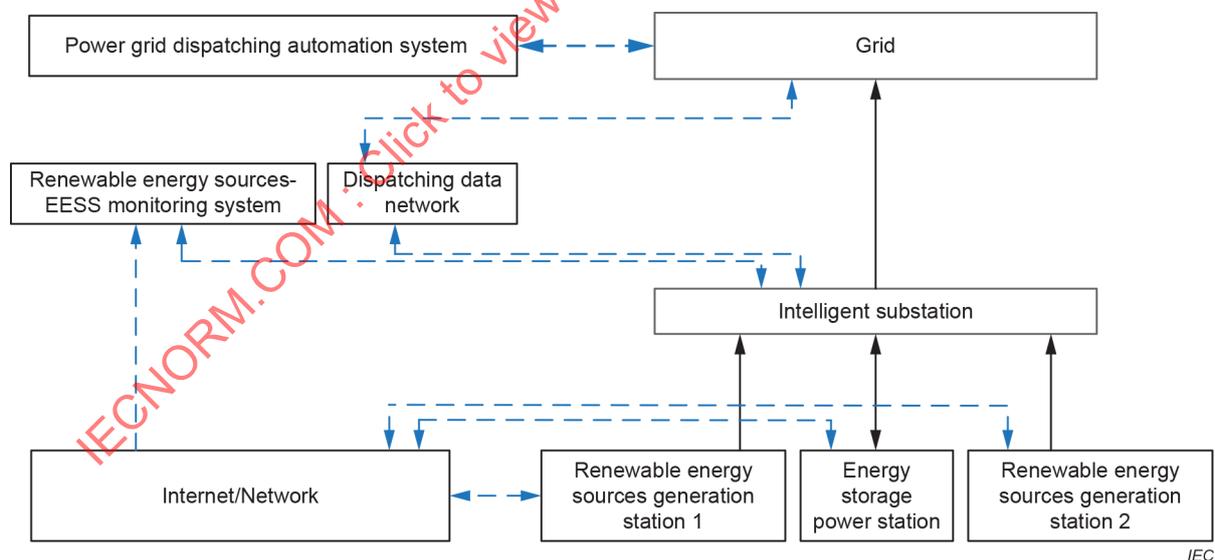
First, the target output of the renewable energy power is obtained. Then, the initial power plan of the energy storage is determined by the target output of the renewable energy power and revised by the energy state feedback control. Finally, the power distribution is performed among the internal units of the energy storage to determine the charging and discharging power commands of each unit. The power smoothing result at the POC shall be checked against any possible grid code requirement for this kind of hybrid power plants. Among other, obtaining the renewable energy power target output and energy state feedback control is the core of the renewable energy power smoothing strategy.

The renewable energy target output refers to the power that is expected after smoothing of the EES system. Renewable energy target output acquisition methods mainly include the following: filtering control algorithms such as first-order filtering, Kalman filtering and wavelet filtering, and other control algorithms such as sliding average, weighted moving average and model predictive control.

The key control parameters of each control algorithm are different, and they affect the target of the renewable energy as well as the smoothing effect of the energy storage system on renewable energy sources.

8.1.5.4   Monitoring

The schematic diagram of the monitoring system for the EES system for the renewable energy sources (power) smoothing is shown in Figure 35. The solid lines in Figure 35 indicate the direction of the power flow. The renewable energy sources generation station supplies electricity to the grid through the substation. The power flow between the energy storage power station and the substation is bidirectional, which represents the charge and discharge behaviour of the energy storage station. The dotted lines indicate the measurement signals and control signals among the renewable energy sources generation station, energy storage power station, substation and monitoring system. Information exchange between the monitoring system and the superior dispatching system is uniformly exported through the substation.

**Figure 35 – Example of the EES system for renewable
energy sources (power) monitoring system**

When the EES system is used to smooth the output of the renewable energy power, the EES system shall operate automatically or remotely in accordance with the target in the scenario. The operating state of the EES system shall be monitored to check whether the remote signal and remote measurement of the EES system are normal.

The information of the voltage, current, active power, reactive power, abnormal alarm and fault of the energy storage unit of the EES system shall be monitored. Information such as abnormal alarms of other equipment shall be monitored.

The functions of the monitoring system shall include SCADA, diagnosis and early warning, panoramic analysis, active and reactive power control, real-time collection of equipment operating status and working parameters, power prediction, uploading of the data to the superior scheduling layer, power distribution based on dispatching command and EES system operation state, and operation mode change.

8.2 Renewable energy sources (energy) generation firming

8.2.1 Applications of the EES systems

8.2.1.1 Functional purpose of the EES systems

The renewable energy sources generation firming application is using an EES system to provide energy to supplement renewable energy generation. The EES system will discharge power when renewable energy generation falls short of the threshold, and charge power when the situation is reversed. The combination output of the EES system and the renewable energy generation shall be steady over a desired time window. The threshold is derived from the forecasted renewable power generation over the desired time window. The time window is commonly between15 min to a few hours.

8.2.1.2 Application related requirements

The selected equipment shall have the following characteristics, to properly deliver the functionality for the application.

a) Reliability of the system's tracking schedule output curve

The degree of matching between the dispatch output curve and the schedule output curve can be expressed by the manhandle distance:

$$z(x,y) = \sum_{i=1}^{N} |x_i - y_i|$$

where

x_i is the value of the dispatch output curve in the ith period;

y_i is the value of the schedule output curve in the ith period;

N is the number of segments per day;

$z(x,y)$ is the manhandle distance between the curves x and y.

b) Energy requirements

Subclause 4.1.2.4 is applicable.

c) Efficiency requirements

Subclause 4.1.2.5 is applicable.

d) Response time and ramp rate requirements

Subclause 4.1.2.6 is applicable.

8.2.2 Conditions and requirements for connection to the grid

Subclause 4.2 is applicable.

8.2.3   Design of the EES systems

8.2.3.1   Structure of the EES systems

Subclause 4.3.2 is applicable.

8.2.3.2   Subsystem specifications

Subclause 4.3.3 is applicable.

8.2.3.3   Grid integration of the EES systems

Subclause 4.3.4 is applicable.

8.2.3.4   Operation and control

The overall idea of the renewable energy sources (energy) generation firming by using the EES system is to track the power generation plan of the power station as the goal, and consider the remaining energy of the EES system, rated power, energy state and other constraints that affect the power output capacity and optimal operation of the EES system. An example of the control strategy for the renewable energy sources (energy) generation firming is as shown in Figure 36.
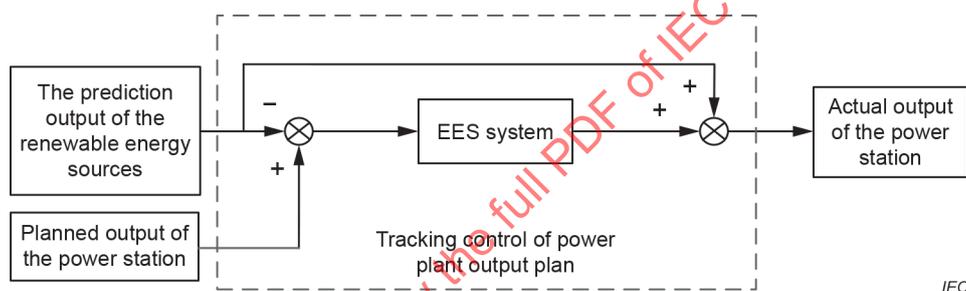
**Figure 36 – Example of control strategy for the renewable
energy sources (energy) firming application**

The operation and control of the EES system should consist of two steps. Firstly, the expected operation value of the EES system is formulated in the power plant output's plan tracking control module. Secondly, the expected operation value of the EES system is corrected in real time in the feedback control module of the EES system. The expected operation value of the EES system is based on the deviation between the short-term prediction value of the power output and the power generation plan of the power station. The real-time output power of the EES system is determined by the rated power and residual energy of the EES system.
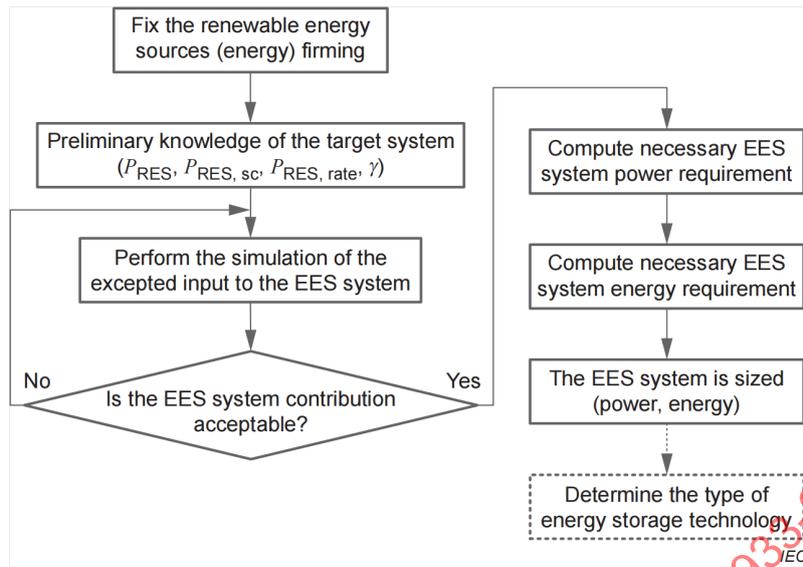
8.2.3.5   Communication interface

Subclause 4.3.8 is applicable.

8.2.4   Sizing and resulting parameters of the EES systems

8.2.4.1   Sizing

a) Sizing process of the EES system

   The general sizing process of the EES system for the renewable energy sources (energy) generation firming is shown in Figure 37.

Figure 37 – Example of EES system sizing process for renewable energy sources (energy) generation firming

NOTE 1   In the figure, P_{RES} is the actual output power of the renewable energy sources; $P_{RES,sc}$ is the scheduled output power of the renewable energy sources; $P_{RES,rate}$ is the rated output of the renewable energy sources; and γ is the coefficient of deviation.

NOTE 2   The actual output of the renewable energy sources after the EES system is within the allowable output range as much as possible. Among other, the renewable energy sources' allowable output interval $[P_{RES,sc}(t)-\gamma P_{RES,rate}, P_{RES,sc}(t)+\gamma P_{RES,rate}]$ is composed of the $P_{RES}(t)$ and the forecast error allowable interval $[-\gamma P_{RES,rate}, \gamma P_{RES,rate}]$. The forecast error allowable interval is mostly taken as the positive and negative deviation γ times the rated output.

b) Requirements for sizing

When performing the sizing process of the EES system, the following requirements shall be met:

- The power supply and storage capacity of the power station shall be considered when determining the sizing of the EES system.

- Different control strategies shall be considered when determining the sizing of the EES system.

- The accumulation subsystem life, charge-discharge characteristics, optimal charge-discharge interval and economy shall be considered when determining the sizing of the EES system.

- The EES power station shall meet the power curve requirements of the dispatch plan. The EES system input and output power shall be compatible with the renewable energy power plant output and the dispatch plan power curve.

- The EES system capacity shall be comprehensively determined according to factors such as the power curve of the dispatch plan, the historical output characteristics of the renewable energy sources, and the seasonal difference of the output power.

8.2.4.2   Characteristics and restrictions of the EES systems

Subclause 4.4.3 is applicable.

8.2.5   Service life of the EES systems

8.2.5.1   Installation

Subclause 4.5.2 is applicable.

8.2.5.2 Performance assessment

Subclause 4.5.3 is applicable.

8.2.5.3 Operation and control

Subclause 8.1.5.3 is applicable.

8.2.5.4 Monitoring

Subclause 8.1.5.4 is applicable.

8.3 EES systems in electric charging stations in combination with renewable energy sources

8.3.1 Applications of EES systems

8.3.1.1 Functional purpose of the EES systems

In combination with the renewable energy source, the EES system is used to absorb electric energy during valley periods and support fast charging load during peak periods, which is effectively reducing load peak-valley difference, eliminating EV charging power demand from the grid, and improving system operation efficiency.

By using the EES system, higher charging power than the maximum power available from the external power grid can be achieved. Higher utilization of renewable energy and higher benefit from day and night price arbitrage can be realized.

8.3.1.2 Application related requirements

The selected equipment shall have the following characteristics, to properly deliver the functionality for the application:

a) Reduction of maximum-minimum load in the period time.

b) Increase of use of renewable energy power generation:

   The use of renewable energy power generation is the ratio of renewable energy use to total energy consumption.

c) Energy requirements

   Subclause 4.1.2.4 is applicable.

d) Efficiency requirements

   Subclause 4.1.2.5 is applicable.

e) Response time and ramp rate requirements

   Subclause 4.1.2.6 is applicable.

8.3.2 Conditions and requirements for connection to the grid

Subclause 4.2 is applicable.

8.3.3 Design of the EES systems

8.3.3.1 Structure of the EES systems

The EES system structure and components defined in 4.3.2 are also applied to the electric charging stations in combination with renewable energy sources applications. In addition, there exist additional considerations. The EES system should be installed in conjunction with renewable energy sources and EV charging piles. An example of the system structure of the EES system in electric charging stations in combination with renewable energy is shown in Figure 38.
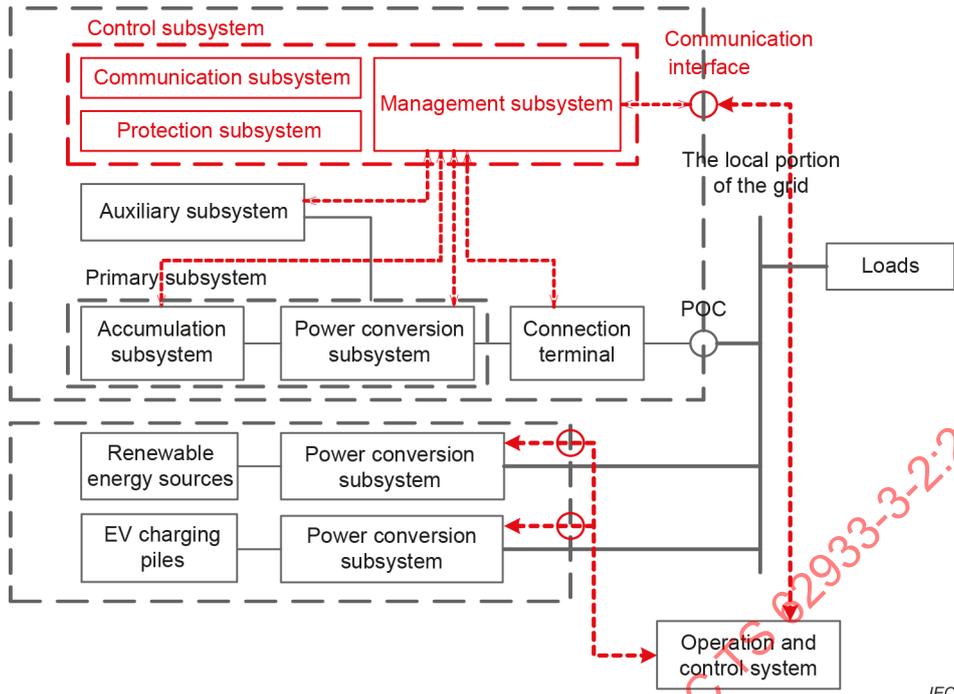
Figure 38 – Example of the system structure of the EES system in electric charging stations in combination with renewable energy sources

8.3.3.2   Subsystem specifications

Subclause 4.3.3 is applicable.

8.3.3.3   Grid integration of the EES systems

Subclause 4.3.4 is applicable.

8.3.3.4   Operation and control

As the charging load fluctuates during 24 h, the EES system can operate at different application modes. The typical application modes include power smoothing mode, load shaping mode and time-of-use price mode. In order to give full play to the advantages of the EES system in various application modes, the segmentation time and segmentation of the EES system charge and discharge mode are based on a comprehensive analysis of the full-day load power.

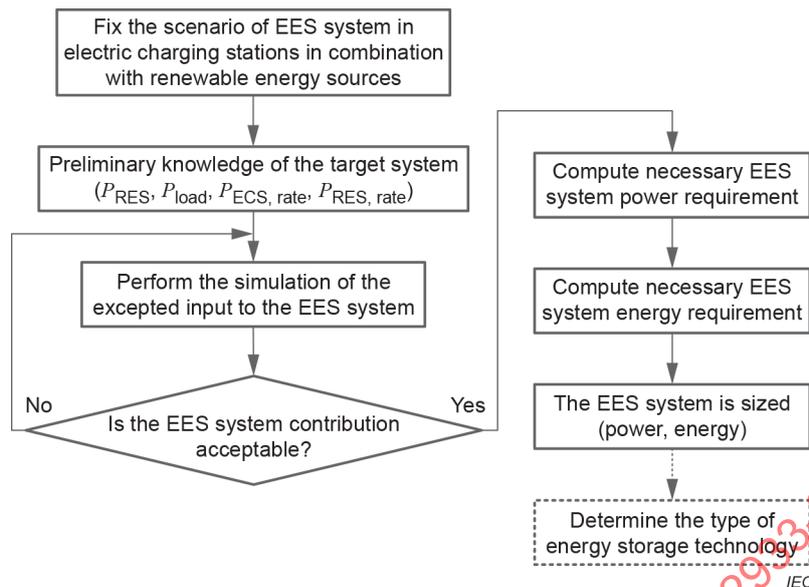### 8.3.3.5   Communication interface

Subclause 4.3.8 is applicable.

8.3.4   Sizing and resulting parameters of the EES systems

8.3.4.1   Sizing

a) Sizing process of the EES system

The general sizing process of the EES system in electric charging stations in combination with renewable energy sources is shown in Figure 39.

Figure 39 – Example of EES system sizing process of the EES system in electric charging stations in combination with renewable energy sources

NOTE   In the figure, P_{RES} is the actual output power of the renewable energy sources; P_{load} is the load power; $P_{ESC,rate}$ is the rated capacity of the electric charging stations; and $P_{RES,rate}$ is the rated output of the renewable energy sources.

b) Requirements for sizing

When performing the sizing process of the EES system, the following requirements shall be met.

- The capacity allocation calculation of the EES system shall consider the accumulation subsystem characteristics, charging-discharging characteristics and the optimal charging- discharging interval and economy.

- The EES system used for load shaping shall be set in accordance with the actual load conditions and the operation mode of energy storage. Depending on the access voltage level, the energy storage stations used for load shaping generally have the following types: 400 V, 10 kV and 35 kV. The grid-connected EES system maximum capacity shall comply with the power level. In China for example, the power level of a 400 V energy storage power station is about 100 kW; the EES system connected to a 10 kV power grid has a power rating of about 1 MW; and the EES system connected to a 35 kV power grid has a power rating of several MW.

- The sustainable discharging time can be based on the peak-to-valley duration of the regional load. The EES system capacity shall be configured according to 5 % to 20 % of the transformer capacity, or determined after calculation.

- The EES system for demand response shall meet the demand response power and time requirements. The EES system capacity shall be determined based on its own operating strategy, demand power and time, and economics.

8.3.4.2   Characteristics and restrictions of the EES systems

Subclause 4.4.3 is applicable.

8.3.5   Service life of the EES systems

8.3.5.1   Installation

Subclause 4.5.2 is applicable.

8.3.5.2   Performance assessment

Subclause 4.5.3 is applicable.

8.3.5.3   Operation and control

After the EV enters the charging station, the charging mode is selected in accordance with the output of each energy unit. When the renewable energy sources output is greater than the load demand, the EV is charged by the renewable energy sources power, and the remaining power is charged to the energy storage or connected to the grid. When the renewable energy sources output does not meet the load demand, it is replenished by the EES system or recharged by the grid. When there is no renewable energy sources output, it is powered by the grid. If the power demand exceeds the grid power supply, the residual load demand is replenished by the energy storage. The specific mode selection is shown in Figure 40.
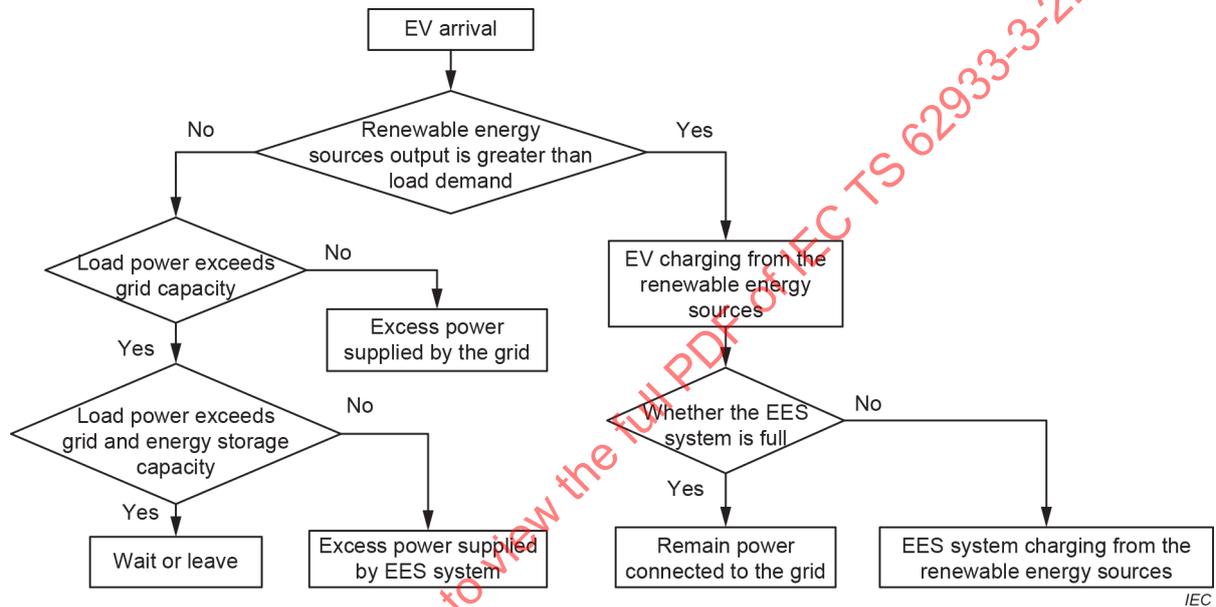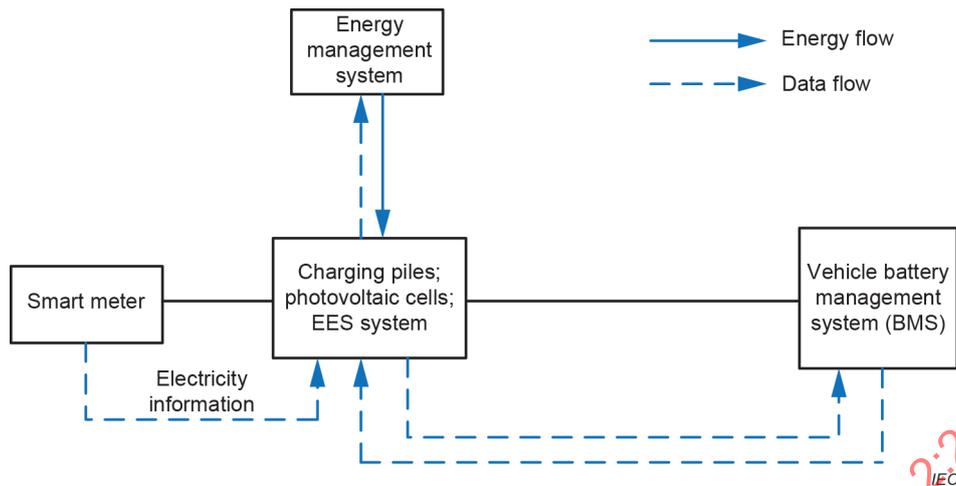

Figure 40 – Example of EV charging mode selection

8.3.5.4   Monitoring

A monitoring system architecture of electric charging stations in combination with renewable energy sources and EES system is shown in Figure 41. Among other, the information interaction between the various systems is shown in Table 3.

Figure 41 – Example of electric charging stations monitoring system architecture in combination with renewable energy sources and EES system

Table 3 – Example of information interaction between various systems

Information collector	Monitoring related information	Communication method/protocol	Information receiving terminal
Smart meter	Electricity information	485 communication	Charging piles; renewable energy sources; EES system
Charging piles; renewable energy sources; EES system	Energy storage capacity; participation time; equipment status; user information, etc.	Ethernet	Energy management system
Energy management system	Charge and discharge command, current, power; timing information	Ethernet	Charging piles; renewable energy sources; EES system
Charging piles; renewable energy sources; EES system	Equipment status; connection status; charge and discharge voltage, current, power; electricity information; working mode; maximum voltage and current limit	CAN communication	Vehicle battery management system (BMS)
Vehicle battery management system (BMS)	User information; working mode; participation time; upper and lower limits of charging and discharging of energy storage; start/stop command; current information of energy storage; charging and discharging voltage; current size; BMS status information maximum/optimal charging and discharging current and time, etc.	CAN communication	Charging piles; renewable energy sources; EES system

9 Power oscillation damping (POD)

9.1 Applications of the EES systems

9.1.1 Functional purpose of the EES systems

In large interconnected electric power systems, some oscillations can cause perturbations in the system. The power oscillation damping is therefore needed to compensate the negative effects that the oscillations can cause in the whole grid operation. The EESS shall improve the damping of power oscillations by means of active power modulation (POD-P) and reactive power modulation (POD-Q), as shown in Figure 42 and Figure 43. However, the POD effect on system stability by the EESS is different due to system structure and characteristics. The capacity allocation calculation of the EES system should consider the accumulation subsystem characteristics, charging-discharging characteristics and the optimal charging-discharging interval and economy. Furthermore, the POD can be performed by several EES systems connected to the grid. This means that POD application will be one of the EES systems' functions and will be superimposed to the regular performance. Therefore, the specific requirements for subsystem specifications have to consider the power and energy ratings coming from the expected EESS contribution to the overall POD policy of the grid operator in addition to the initial ones coming from other EESS applications. The response time and ramp rate for POD application have to be checked and considered when adding the POD controller to an EESS.
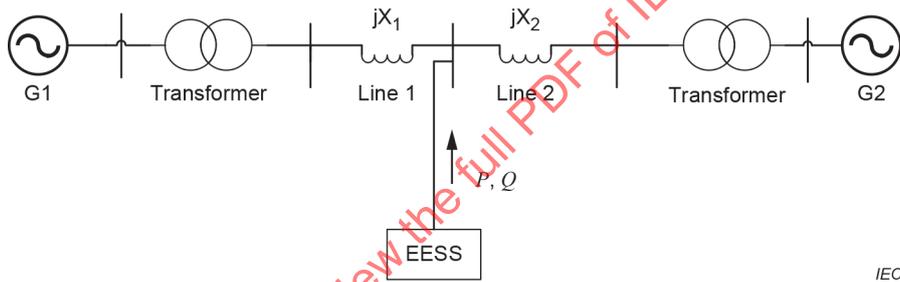

Figure 42 – Schematic diagram of the system structure of a single infinite bus system connected with the EES system
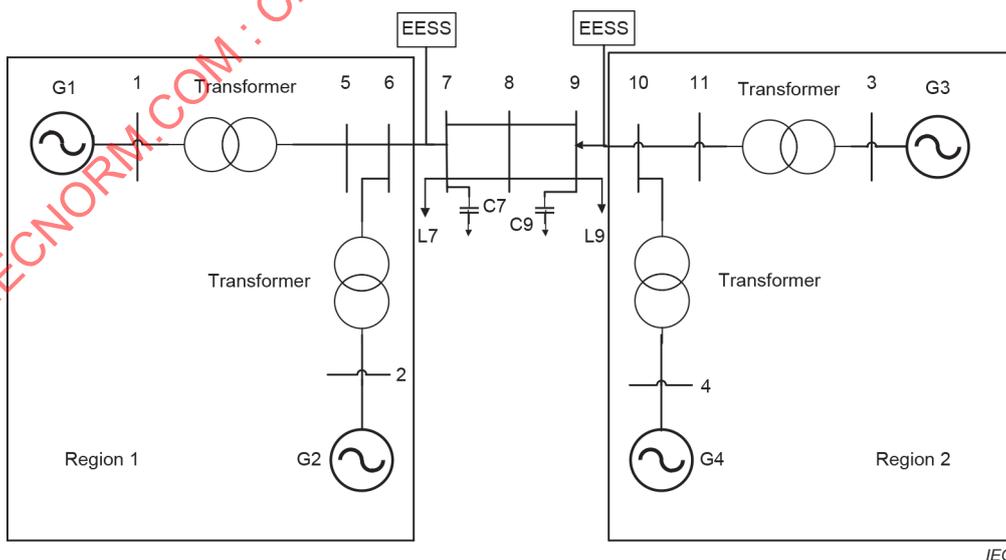

Figure 43 – Schematic diagram of typical four-generators two-regions system structure connected with the EES system

The types of oscillations to be considered are:

a) Electromechanical oscillations (local and inter-area) which can occur due to weak links among power systems or generators. The oscillations involve power exchanges but also voltage and current oscillations that can cause tripping of lines or generators and thus lead to severe disturbances.

b) Other oscillations caused by SSR (subsynchronous resonance) can be considered. SSR can appear in series compensated overhead lines or HVDC (mainly LCC, line-commutated converter). Another similar oscillation is subsynchronous interaction between power electronics connected generation (PV and wind) and series compensated overhead lines and/or HVDC (mainly LCC).

c) Oscillations linked to power electronics connected generation (PV and wind) connected to a weak system, with a very low short-circuit ratio (SCR = short-circuit capacity (SCC_{POC}) / rated power of power plant ($P_{n, \text{power plant}}$). The frequency oscillation can be between 4 Hz to 35 Hz.

d) Forced oscillation, due to control interaction.

9.1.2 Application related requirements

For the above four oscillation modes, the EES system can provide the required POD-P and POD-Q to improve system damping according to oscillation frequency, time cycle and other system characteristics.
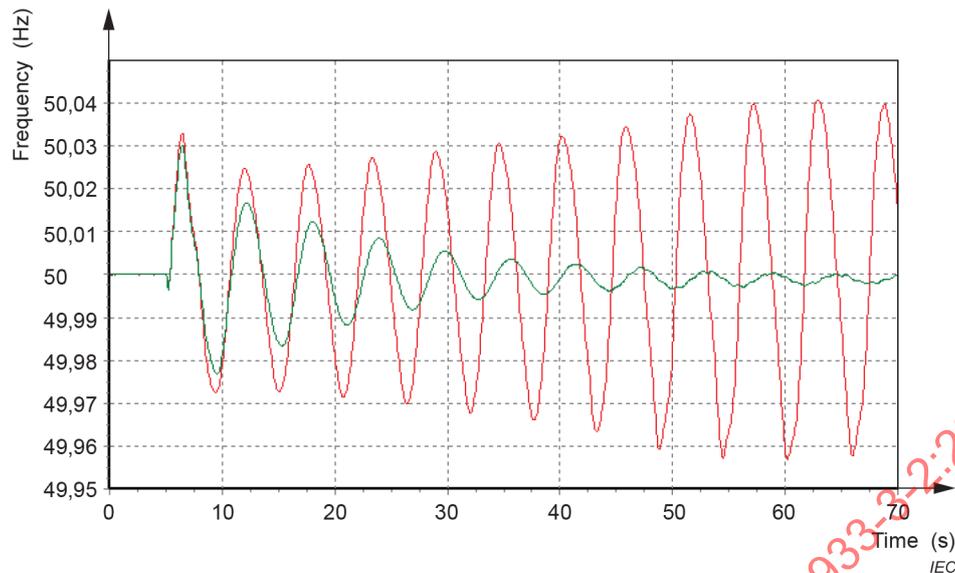
a) Electromechanical oscillations

The damping of the oscillations with the POD control will help to improve the small signal stability as well as the oscillations caused by big disturbances. Typical values of frequency for these oscillations are between 0,01 Hz and 0,5 Hz in case of inter-area oscillations and between 0,5 Hz and 3 Hz in case of local oscillations.

In the case of an under-damped power system, any minor disturbance can cause the machine angle to oscillate around its steady-state value at the natural frequency of the electromechanical system. The angle oscillation, of course, results in a corresponding power oscillation around the steady-state power being transmitted. The lack of sufficient damping can be a major problem in some power systems and, in some cases, it can be the limiting factor for the transmittable power.

These oscillations can occur also in the event of big disturbances, for instance, in the event of short-circuits after the clearing of the fault.

Since power oscillation is a sustained dynamic event, it is necessary to vary the applied active power and reactive power compensation to counteract the accelerating and decelerating swings of the disturbed machine(s), and therefore, to damp the oscillations of power, frequency and voltage in the system.

Figure 44 shows the evolution of the simulation of the power oscillation with (in green) and without (in red) five BESS$_S$ properly placed in a transmission grid.

**Figure 44 – Example of damping power oscillation simulation
with five BESSs in a transmission grid**

b) SSR and SSI oscillations

Oscillations can appear due to resonances between the electrical power system and the mechanical system of the synchronous generators (SSRs). The electrical frequency of the oscillation can be between 15 Hz and 35 Hz in a 50 Hz frequency system. In this case, the EES system should be intended for very short response time, since the output power should change in, for example, (1/30 Hz) = 33 ms. In this case, POD-Q is preferred, since it will not stress the accumulation subsystem, but the number of times can be considered when damping is needed for POD-P (fast ageing to be avoided).

Also, oscillations can appear between power plants connected by power electronics and the power system (subsynchronous interaction, SSI).

c) Linked to power electronics (PV + wind, etc.) generation

Oscillations can appear between generation connected by power electronics and the grid or between several power electronics connected power plants, due to weakness of the power system in the POC.

d) Forced oscillations

Oscillations can appear due to problems in the power plant controls.

9.2 Conditions and requirements for connection to the grid

Subclause 4.2 is applicable.

Additionally, when damping inter-area oscillations, the EES system can be required to properly receive and process remote phase measurement unit (PMU) signals and fulfil the corresponding requirements coming from the grid codes.

9.3 Design of the EES systems

9.3.1 Structure of the EES system

The EES system for the POD should consider a very accurate measure of frequency and voltage, not only at the POC but also at a remote location that will serve as reference for the whole power grid when performing POD as a coordinate strategy. Therefore, additional components such as phase measurement units (PMUs) could be needed, and appropriate communication systems for not only control dispatch communication but also for remote frequency and power acquisition will be required in accordance with IEC/IEEE 60255-118-1 or similar standards, when the observability at the POC has to be improved if possible.