

TECHNICAL SPECIFICATION



**Microgrids –
Part 3-1: Technical requirements – Protection and dynamic control**

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IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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TECHNICAL SPECIFICATION



**Microgrids –
Part 3-1: Technical requirements – Protection and dynamic control**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

MICROGRIDS –

Part 3-1: Technical requirements – Protection and dynamic control

FOREWORD

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- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62898-3-1, which is a Technical Specification, has been prepared by IEC subcommittee 8B: Decentralized Electrical Energy Systems of IEC technical committee 8: System aspects of electrical energy supply.

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

Draft TS	Report on voting
8B/53/DTS	8B/59/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62898 series, published under the general title *Microgrids*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://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- withdrawn,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

Microgrids can serve different purposes depending on the primary objectives of their applications. They are usually seen as a means to manage reliability of supply in a grid contingency and to facilitate local optimization of energy supply by controlling distributed energy resources (DER). Microgrids also present a way to provide electricity supply in remote areas, to use renewable energy as a systematic approach for rural electrification and to increase resiliency and security of supply to end users.

Deployment of DER can cause a microgrid or distribution system of a grid to face several challenges, including fault protection and dynamic control issues. There are, however, some issues commonly faced in the protection and control of microgrids which are less prevalent in large grids. These issues include: bidirectional flow of power resulting in voltage excursions outside acceptable limits, fault current being supplied from multiple sources, loss of synchronism between multiple sources when a fault occurs, potentially limited fault current magnitude, lower inertia or lower primary time constant, regular changes in operational configuration due to economic optimization, and intermittency of source-dependent renewable distributed generators. These issues worsen when the microgrid contains several converter-based generators (CBGs) and operates in island mode. As such, conventional protection and control strategies may not be suitable or sufficient for microgrids. Protection systems different from the conventional ones may be required. In some instances, protection systems may need to be adjusted dynamically based on the operating state of the microgrid.

Conventional power systems have predominantly consisted of power sources, such as fossil fuel-fired thermal power plants, hydro power plants and nuclear power plants, which are relatively stable and easy to control. On the other hand, microgrids often contain many different types of sources, many of which are intermittent. Hence, protection and dynamic control in microgrids need to be more sophisticated than in conventional power systems. However, the main grid contributes to the fault currents in the grid-connected mode of operation and hence the fault currents are large enough to actuate conventional protection devices. Though it is possible to employ conventional protection principles and existing standards for the protection of microgrids operating in grid-connected mode, the existing protection settings should be systematically assessed as the existence of DER may compromise the coordination of the protection system.

Due to the specific characteristics of microgrids and their frequent use of converter-based generators, disturbances in microgrids require special consideration. The disturbance problems in microgrids can be addressed by dynamic control. Dynamic control can be classified as transient disturbance control and dynamic disturbance control. Transient disturbance control damps disturbances in microgrids caused by forced or unintended sudden and severe voltage and current changes due to switching of large sources or loads, mode transfer or fault clearance, and characterized by large magnitude and phase change and with a time duration of milliseconds. Dynamic disturbance control regulates disturbances in microgrids caused by forced or unintended voltage and current changes due to generator and load variation, and characterized by magnitude and phase changes beyond the normal operating limits, and continuing for milliseconds to seconds.

The initial characteristics of faults are very similar to initial characteristics of transient and dynamic disturbances. Distinguishing the two types of incidents from each other is critical for the proper operation of microgrids. Thus, protection and dynamic control of microgrids are closely related and need to be coordinated with each other.

This part of IEC 62898 specifies requirements to address the above-mentioned protection and dynamic control issues in microgrids.

IEC TS 62898 (all parts) intends to provide general guidelines and technical requirements for microgrids.

a) IEC TS 62898-1 mainly covers the following issues:

- determination of microgrid purposes and application;
- preliminary study necessary for microgrid planning, including resource analysis, load forecast, DER planning and power system planning;
- principles of microgrid technical requirements that should be specified during planning stage;
- microgrid evaluation to select an optimal microgrid planning scheme.

b) IEC TS 62898-2 mainly covers the following issues:

- operation requirements and control targets of microgrids under different operation modes;
- basic control strategies and methods under different operation modes;
- requirements of energy storage, monitoring and communication under different operation modes;
- power quality.

c) IEC TS 62898-3-1 mainly covers the following issues:

- requirements for microgrid protection;
- protection systems for microgrids;
- dynamic control for transient and dynamic disturbances in microgrids;

Microgrids can be stand-alone or a sub-system of an interconnected grid. The technical requirements in this Technical Specification are intended to be consistent with:

- 1) IEC 60364-7 (all parts and amendments related to low-voltage electrical installations);
- 2) IEC TS 62786, requirements for connection of generators intended to be operated in parallel with the grid;
- 3) IEC TS 62257 (all parts) with respect to rural electrification;
- 4) IEC TS 62749 with respect to power quality;
- 5) IEC TS 62898-1;
- 6) IEC TS 62898-2;
- 7) IEC TS 63268;

MICROGRIDS –

Part 3-1: Technical requirements – Protection and dynamic control

1 Scope

The purpose of this part of IEC 62898 is to provide guidelines for the specification of fault protection and dynamic control in microgrids. Protection and dynamic control in a microgrid are intended to ensure safe and stable operation of the microgrid under fault and disturbance conditions.

This document applies to AC microgrids comprising single or three-phase networks or both. It includes both isolated microgrids and non-isolated microgrids with a single point of connection (POC) to the upstream distribution network. It does not apply to microgrids with two or more points of connection to the upstream distribution network, although such systems can follow the guidelines given in this document. This document applies to microgrids operating at LV or MV or both. DC and hybrid AC/DC microgrids are excluded from the scope, due to the particular characteristics of DC systems (extremely large fault currents and the absence of naturally occurring current zero crossings).

This document defines the principles of protection and dynamic control for microgrids, general technical requirements, and specific technical requirements of fault protection and dynamic control. It addresses new challenges in microgrid protection requirements, transient disturbance control and dynamic disturbance control requirements for microgrids. It focuses on the differences between conventional power system protection and new possible solutions for microgrid protection functions.

Depending on specific situations, additional or stricter requirements can be defined by the microgrid operator in coordination with the distribution system operator (DSO).

This document does not cover protection and dynamic control of active distribution systems. This document does not cover product requirements for measuring relays and protection equipment.

This document does not cover safety aspects in low voltage electrical installations, which are covered by IEC 60364 (all parts and amendments related to low-voltage electrical installations). Requirements relating to low voltage microgrids can be found in IEC 60364-8-2.

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 60364 (all parts), *Low voltage electrical installations*

3 Terms and definitions

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

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

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

3.1

code

<electric power system> collection of rules concerning rights and duties of the parties involved in a certain part of the electric power system

EXAMPLE Grid code, distribution code.

[SOURCE: IEC 60050-617:2009, 617-03-03]

3.2

(electronic) (power) converter

(electronic) (power) convertor

operative unit for electronic power conversion, comprising one or more electronic valve devices, transformers and filters if necessary and auxiliaries if any

Note 1 to entry: In English, the two spellings "convertor" and "converter" are in use, and both are correct. In this document, the spelling "converter" is used in order to avoid duplications.

[SOURCE: IEC 60050-551:1998, 551-12-01, modified – The figure has been deleted.]

3.3

converter-based generator

CBG

generator of AC power that is naturally a DC source, or an AC source whose frequency is different from the power frequency, and is connected to the electric power system through a power converter

3.3.1

grid-forming CBG

generator which is connected to the network through a converter that can be controlled as a voltage source capable of controlling voltage and frequency of the network

Note 1 to entry: There are also stiff grid-forming CBGs which are a special type of grid-forming CBGs delivering power at constant frequency and voltage.

3.3.2

grid-supporting CBG

generator which is connected to the network through a converter with a power source capable of actively assisting the regulation of voltage and frequency of the network

3.3.3

grid-following CBG

generator which is connected to the network through a converter with a power source that does not have the capability to actively assist the regulation of voltage and frequency of the network

3.4

distributed energy resources

DER

generators (with their auxiliaries, protection and connection equipment), including loads having a generating mode (such as electrical energy storage systems), connected to a low-voltage or a medium-voltage network

[SOURCE: IEC 60050-617:2017, 617-04-20]

3.5

distributed generation
embedded generation
dispersed generation
DG

generation of electric energy by multiple sources which are connected to the power distribution system

[SOURCE: IEC 60050-617:2009, 617-04-09, modified – "distributed generation" has been listed as a first preferred term and the abbreviated term "DG" has been added.]

3.6

distribution system operator
distribution network operator
distributor
DSO

party operating a distribution system

[SOURCE: IEC 60050-617:2009, 617-02-10, modified – The abbreviated term "DSO" has been added.]

3.7

dynamic disturbance

<microgrid> series of voltage and current changes in a microgrid caused by output of renewable energy sources reaching a sufficiently high proportion, non-linear loads, intentional islanding, intermittency and output power fluctuation of renewable energy resources and grid side faults, which continue for a period of 50 ms to 2 s

3.8

electrical energy storage
EES

installation able to absorb electrical energy, to store it for a certain amount of time and to release electrical energy during which energy conversion processes may be included

EXAMPLE A device that absorbs AC electrical energy to produce hydrogen by electrolysis, stores the hydrogen, and uses that gas to produce AC electrical energy is an electrical energy storage.

Note 1 to entry: The term "electrical energy storage" may also be used to indicate the activity that an apparatus, described in the definition, carries out when performing its own functionality.

Note 2 to entry: The term "electrical energy storage" should not be used to designate a grid-connected installation, "electrical energy storage system" is the appropriate term.

[SOURCE: IEC 62933-1:2018, 3.1]

3.8.1

energy intensive application

EES system application generally not very demanding in terms of step response performances but with frequent and long charge and discharge phases at variable discharge powers

Note 1 to entry: Reactive power exchange with the electric power system is frequently present together with active power exchange.

[SOURCE: IEC 62933-1:2018, 3.12, modified – "energy intensive application" has been listed as a preferred term instead of an admitted term, "frequent" has been added in the definition, "may be present" has been replaced with "is frequently present" in Note 1 to entry and Note 2 to entry has been deleted.]

3.8.2**power intensive application**

EES system application generally demanding in terms of step response performances and with frequent charge and discharge phase transition or with reactive power exchange with the electric power system

[SOURCE: IEC 62933-1:2018, 3.13, modified – "power intensive application" has been listed as a preferred term instead of an admitted term and the note has been deleted.]

3.9**fault ride-through****FRT**

ability of a generating unit or power plant to stay connected during specified faults in the electric power system

3.10**high voltage****HV**

- 1) in a general sense, the set of voltage levels in excess of low voltage
- 2) in a restrictive sense, the set of upper voltage levels used in power systems for bulk transmission of electricity

[SOURCE: IEC 60050-601:1985, 601-01-27]

3.11**island**

<power system> portion of a power system, that is disconnected from the remainder of the system, but remains energized

[SOURCE: IEC 60050-603:1986, 603-04-46]

3.11.1**intentional island**

island resulting from planned action(s) of automatic protections, or from deliberate action by the responsible network operator, or both, in order to keep supplying electrical energy to a section of an electric power system

[SOURCE: IEC 60050-617:2017, 617-04-17]

3.11.2**unintentional island**

island that is not anticipated by the relevant network operator

[SOURCE: IEC 60050-617:2017, 617-04-18]

3.12**low voltage****LV**

set of voltage levels used for the distribution of electricity and whose upper limit is generally accepted to be 1 000 V for alternating current

[SOURCE: IEC 60050-601:1985, 601-01-26]

3.13**medium voltage****MV**

any set of voltage levels lying between low and high voltage

Note 1 to entry: The boundaries between medium- and high-voltage levels overlap and depend on local circumstances and history or common usage. Nevertheless the band 30 kV to 100 kV frequently contains the accepted boundary.

[SOURCE: IEC 60050-601:1985, 601-01-28]

3.14

microgrid

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

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

[SOURCE: IEC 60050-617:2017, 617-04-22]

3.14.1

isolated microgrid

stand-alone microgrid

group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that cannot be connected to a wider electric power system

Note 1 to entry: Isolated microgrids are usually designed for geographical islands or for rural electrification.

[SOURCE: IEC 60050-617:2017, 617-04-23]

3.14.2

non-isolated microgrid

group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that can be connected to a wider electric power system

[SOURCE: IEC 60050-617:2017, 617-04-23, modified – The definition is a modification of that of "isolated microgrid" (3.14.1).]

3.15

over-voltage ride-through OVRT

ability of a generating unit or power plant to stay connected during a limited duration rise of system voltage

Note 1 to entry: In some documents the expression "High Voltage Ride Through (HVRT)", is used for the same capability.

3.16

phase locked loop

PLL

feedback circuit for synchronizing an oscillator with the phase of an input signal

[SOURCE: IEC 60050-713:1998, 713-10-48]

3.17

point of connection

POC

reference point on the electric power system where the user's electrical facility is connected

[SOURCE: IEC 60050-617:2009, 617-04-01]

3.18**power quality**

characteristics of the electric current, voltage and frequencies at a given point in an electric power system, evaluated against a set of reference technical parameters

Note 1 to entry: These parameters might, in some cases, relate to the compatibility between electricity supplied in an electric power system and the loads connected to that electric power system.

[SOURCE: IEC 60050-617:2009, 617-01-05]

3.19**power system stability**

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

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

3.20**protection system**

arrangement of one or more protection equipments, and other devices intended to perform one or more specified protection functions

Note 1 to entry: A protection system includes one or more protection equipments, instrument transformer(s), wiring, tripping circuit(s), auxiliary supply(s) and, where provided, communication system(s). Depending upon the principle(s) of the protection system, it may include one end or all ends of the protected section and, possibly, automatic reclosing equipment.

Note 2 to entry: The circuit-breaker(s) are excluded.

[SOURCE: IEC 60050-448:1995, 448-11-04]

3.20.1**dependability of protection**

probability for a protection of not having a failure to operate under given conditions for a given time interval

[SOURCE: IEC 60050-448:1995, 448-12-07, modified – The figure has been deleted.]

3.20.2**reliability of protection**

probability that a protection can perform a required function under given conditions for a given time interval

Note 1 to entry: The required function for protection is to operate when required to do so and not to operate when not required to do so.

[SOURCE: IEC 60050-448:1995, 448-12-05, modified – The figure has been deleted.]

3.20.3**security of protection**

probability for a protection of not having an unwanted operation under given conditions for a given time interval

[SOURCE: IEC 60050-448:1995, 448-12-06, modified – The figure has been deleted.]

3.20.4**selectivity of protection**

ability of a protection to identify the faulty section and/or phase(s) of a power system

[SOURCE: IEC 60050-448:1995, 448-11-06]

3.20.5

unwanted operation of protection

operation of a protection either without any power system fault or other power system abnormality, or for a system fault or other power system abnormality for which that protection should not have operated

[SOURCE: IEC 60050-448:1995, 448-12-03]

3.21

reliability

<electric power system> probability that an electric power system can perform a required function under given conditions for a given time interval

Note 1 to entry: Reliability quantifies the ability of an electric power system to supply adequate electric service on a nearly continuous basis with few interruptions over an extended period of time.

Note 2 to entry: Reliability is the overall objective in electric power system design and operation.

[SOURCE: IEC 60050-617:2009, 617-01-01]

3.22

stability

<electric power system> capability of a power system to regain or to retain a steady-state condition, characterized by the synchronous operation of the generators and/or a steady acceptable quality of the electricity supply, after a disturbance due, for example, to variation of power or impedance

[SOURCE: IEC 60050-603:1986, 603-03-01, modified – "or to retain a steady state condition" and " and/or a steady acceptable quality of the electricity supply" have been added.]

3.23

stability

<microgrid> capability of a microgrid to regain a steady state after being subjected to a disturbance without involuntary load shedding

3.24

stability zone

operating area situated within the stability limits of the system state variables

[SOURCE: IEC 60050-603:1986, 603-03-12]

3.25

total harmonic ratio

total harmonic distortion

THD

ratio of the RMS value of the harmonic content to the RMS value of the fundamental component or the reference fundamental component of an alternating quantity

Note 1 to entry: The total harmonic ratio depends on the choice of the fundamental component. If it is not clear from the context which one is used an indication should be given.

Note 2 to entry: The total harmonic ratio may be restricted to a certain harmonic order. This is to be stated.

[SOURCE: IEC 60050-551:2001, 551-20-13]

3.26

transient disturbance

<microgrid> sudden and severe voltage and current changes in a microgrid caused by switching of generation or load, unintentional islanding or faults, characterized by large magnitude and phase changes and continuing for a period of 0 ms to 50 ms

3.27

transient stability of a power system

power system stability in which disturbances may have large rates of change and/or large relative magnitudes

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

3.28

under voltage ride-through

UVRT

ability of a generating unit or power plant to stay connected during a limited duration dip of system voltage

Note 1 to entry: In some documents the expression "Low Voltage Ride Through (LVRT)", is used for the same capability.

4 Microgrid protection requirements

4.1 General

With conventional grids, the protection strategy depends on many factors and the complexity of the protection systems can be very different in different applications. For example, protection systems are different in residential LV grids from those used in meshed transmission grids. The protection strategy in microgrids depends on many factors. The main factors are as follows.

- a) Protection systems shall be adapted to the voltage level of the microgrid:
 - microgrids based on LV networks: for example, residential house, building, rural electrification (access to energy);
 - microgrids with MV and LV distribution networks: for example, a campus with several buildings and MV links between buildings, remote industrial plants, geographical islands with an MV distribution network between substations.
- b) Protection systems depend on the microgrid architecture. In traditional grids, protection systems are closely linked to the grid architecture (meshed grid, closed or open ring, radial structure, etc.). For microgrids, its electrical structure also has an impact on the protection system complexity. For example, a microgrid where all the sources are connected to the same busbar is easier to protect than a microgrid with distributed generators on several busbars. The grid architecture and the locations of the power sources can significantly affect the complexity and therefore the reliability and cost of the protection system. Thus, the protection system design shall be considered at the same time as the grid architecture.
- c) Protection systems are designed to meet specified reliability and availability requirements of the power system. The protection strategy, in particular the fault selectivity, is a key factor to reach the required availability level for a given microgrid, but these technical requirements shall be balanced against the corresponding cost of the protection equipment.
- d) Protection equipment commercially available on the market is not the same for MV and LV applications:
 - Multifunctional protection relays, which are commonly used in MV/HV grids, can be used to implement complex protection systems. These devices can provide several protection functions, an internal customized logic, and different setting groups, which can typically be changed remotely via the relay's communication link. Complementary to the protection relay, measuring sensors (current transformers, voltage transformers, temperature sensors, etc.) and (in most cases) a reliable DC power supply system are essential parts of the protection system.

- At LV levels, simpler protection functions are often embedded in LV circuit-breakers. However, protection systems shall also meet specific requirements linked to safety and based on local regulations or international standards (e.g. IEC 60364 (all parts)). In specific cases (e.g. point of connection to MV level, critical infrastructure), protection of parts of the LV network can be based on MV protection relays to cover complex protection systems. This option is already used for conventional grids.
- e) Microgrid protection systems are particularly impacted by the short-circuit current levels. Due to different operation modes (grid-connected and island) and the availability and control of distributed generators, the short-circuit current level and characteristics could vary greatly at any point within the microgrid. If synchronous generators are continuously operating, for example in hydropower or biogas plants, the short-circuit current should be large enough to make conventional protection effective. In the case of isolated microgrids, or non-isolated microgrids operating in island mode, and which are served only by converter-based generators, the short-circuit current is often low. In these cases, the generators might be able to provide sufficient current to operate an overcurrent protection device with a lower current setting but not those with a higher setting. The design of the microgrid protection system needs to consider the short-circuit current from generators within the microgrid and impact of the different operational modes.

4.2 Main requirements specific to microgrids

4.2.1 General

Microgrids can have a number of specific requirements in comparison with conventional grids. Protection of microgrids with a high proportion of conventional synchronous machines (e.g. geographical islands or industrial plants fed by conventional gensets) may resemble that of conventional grids. However, microgrids with a higher proportion of converter-based-generators have specific requirements that need to be considered.

4.2.2 Phase fault protection

In microgrids, phase fault detection is challenging due to the following issues:

- a) Fault current contribution from multiple in-feeds
Conventional MV and LV power systems are typically operated in such a way that only unidirectional short-circuit current flow occurs, i.e. they only have a single short-circuit source (neglecting the contributions from motors). In microgrids, short-circuit sources can be distributed at different locations. Such multiple generators are common in existing HV transmission systems where more sophisticated protection systems are used, for example distance protection and differential protection. This point will be developed in Clause 5, but such protection systems are not always applicable to MV or LV levels of microgrids with respect to economic constraints, except for the specific application requirements.
- b) Low short-circuit current magnitude
In microgrids, the proportion of converter-based generation (wind, PV, EES, etc.) is often much higher than in conventional power systems. Grid-forming converters allow microgrids to be operated with only converter-based generators, without any conventional synchronous machines. With converter-based generators, the short-circuit current is generally only slightly above the rated current of the converter, whereas a synchronous machine can provide three to five times its rated current. Depending on the operating mode, the minimum short-circuit current could be close to or even below the maximum load current, especially for feeders close to main busbars (where sources are connected) or feeders between busbars with distributed generators connected. This is not generally an issue for feeders supplying smaller loads, as the ratio between the minimum short-circuit current and the rated load current is high enough to allow discrimination between fault and load currents. For details on the use of conventional phase overcurrent protection in microgrids, especially for LV microgrids, see 5.2.1.2.
- c) Microgrids can be operated in many operating modes
For non-isolated microgrids, there are two main modes – grid-connected mode or island mode. Fault detection and selectivity shall be ensured for microgrids operating in either of the two modes, considering the specific generator connection scheme and all possible operating scenarios (see 4.5).

4.2.3 Earth fault protection

The earth fault protection system is directly linked to the earthing system. The protection system shall be designed according to the earthing system (as in conventional grids). The following points should be considered in earth fault protection of microgrids.

- a) The earthing system shall be managed in all possible operating modes.
 - For non-isolated microgrids:
 - in grid-connected mode, the earthing system is generally defined by the grid and the protection system is generally based on the same principles as the grid, with selectivity between the grid protection and the microgrid protection.
 - in island mode, if the earthing connection is located inside the main grid, above the POC, the earthing connection may be lost and the islanded microgrid will operate as an (unwanted) unearthed system. According to the earthing system defined for the island mode, a new earthing connection could be required inside the islanded microgrid. In any case, it is recommended to have the neutral to earth connection in one single location (as required in IEC 60364 (all parts) for LV installations) to facilitate fault detection and selectivity.
 - For isolated microgrids, the earthing system shall be designed to ensure that it remains functional in all possible configurations. If the microgrid is divided into several sub-parts after protection actions (e.g. the trip of a feeder between two source busbars), one or more of the sub-parts could eventually become un-earthed. Such a scenario shall be considered by the protection system, for example setting up a new earthing system, generator disconnection (part-system shut-down) or use of specific protection for the now un-earthed part.
- b) Depending on the selected earthing system, earth fault detection and selectivity may be simpler than for phase faults. When the neutral is earthed at a single location (most of the use cases), this single neutral-to-earth connection is the only path for the earth fault current (residual current). Fault detection can hence be ensured by use of conventional residual overcurrent, and selectivity can be achieved with a basic time selectivity. Even if converter-based generators have low levels of earth fault current, the use of sensitive earth fault overcurrent protection is sufficient to meet the sensitivity requirements.
- c) For all LV microgrids the earth fault protection shall meet the sensitivity and operation time required by local regulations or international standards (IEC 60364 (all parts), IEC 60364-4-41 and IEC 60364-8-2 in particular).
- d) IEC 60364 (all parts) (in particular IEC 60364-8-2) addresses the particular issue of an earthing system change between grid-connected mode (earthing system defined by the grid) and island mode (with an earthing system which could be different from the grid, e.g. TT with grid and TN-S for islanded microgrid, but other combinations are possible).

4.3 General protection requirements

4.3.1 General

General requirements are applicable to all protection systems, both conventional grids and microgrids. Some of these requirements are expanded to address specific requirements for microgrids.

4.3.2 Dependability of protection

Dependability of protection is the probability of not having a failure to operate. This can generally be achieved by satisfying two main requirements:

- a) ensuring adequate protection sensitivity;
- b) implementing a protection system with two independent protection levels (backup protection function).

All faults inside a microgrid shall be cleared in all possible operating modes.

- 1) For phase faults, a minimum sensitivity shall be ensured to detect an insulation failure and avoid the risk of fire. In the event of insulation failure in cables or electrical equipment, even if the short-circuit current is limited by the short-circuit power of converter-based generators, and the magnitude is close to the rated level, an insulation failure fed by a "rated" current becomes a hot spot with a risk of high temperatures and the potential to start a fire. So even if short-circuit currents are small due to the limited short-circuit current rating of the generators, an insulation failure between phases or phase to neutral/earth shall be detected, with an operating time shorter than thermal overload protection (of the cable, line, motor, transformer, generator, etc.). Typically, a fault clearing time shorter than 5 s is recommended for these low short-circuit currents (which are not overload currents).
- 2) For earth faults, a minimum sensitivity shall be ensured to meet the requirements for the maximum step and touch voltages defined by local regulations or international standards. Generally, this requirement is defined by a maximum voltage (or current for a given maximum earthing resistance) and associated maximum clearing time.

To ensure the appropriate level of safety, protection systems shall normally provide two levels, a main protection function and a backup protection function. Generally, the main protection clears the fault with the right selectivity, while the backup protection could be managed with a reduced selectivity after a time delay. In MV or LV systems, with conventional unidirectional short-circuit current flow, the backup protection is ensured by the protection stage at the upstream level or a general backup protection based on voltage measurement at the source level. In HV systems, the backup protection is ensured with two independent main protection systems to ensure a high safety and availability level.

4.3.3 Security of protection

Security of protection is the probability of not having an unwanted operation. Protection systems used in microgrids shall remain stable (no unwanted operation) during disturbance events, such as those described in Clause 6.

For non-isolated microgrids in grid-connected mode, protection functions inside the microgrid shall remain stable in the event of disturbances in the main grid. Local grid codes or regulations normally define requirements for fault ride-through (FRT), such as under/over voltage ride-through (UVRT/OVRT) or frequency ride-through. FRT can be defined for voltage and frequency disturbances. The aim is to ensure the stability of loss of mains (anti-islanding) protection, which can be located at the POC or in each generator protection. The ride-through requirements are applicable to all kinds of protection inside the microgrids located between the POC and the generators, because all the distributed sources shall remain connected to the main grid during these disturbances.

4.3.4 Availability and selectivity of protection

In the event of a fault inside a microgrid, the faulted equipment shall be isolated with the correct selectivity to ensure continuity of service of the remaining system, facilitate fault location and reduce repair time.

For a single infeed feeder, the protection system should trip only the circuit-breaker located just upstream of the fault location. In the case of a double infeed feeder, the protection system shall trip the two circuit-breakers at both ends of the faulted feeder. In general, all circuit-breakers of all in-feeds to the fault shall be tripped to isolate the fault.

Selectivity of protection systems for microgrids can be ensured differently according to the operating mode and configurations of the microgrid. Three different protection selectivity levels can be defined inside a microgrid.

- a) High level, where safety and availability are fully ensured: All faults are detected and cleared with full selectivity. This level shall be required for the most common operating modes (e.g. grid-connected mode or island mode with the most common generation conditions).

- b) Medium level, where safety is ensured but availability is not fully ensured: All faults are detected but are cleared with partial selectivity (not limited to the faulted feeder). This level could be used for island mode for some combinations of operating generators.
- c) Low level, where safety is ensured but availability is not ensured: All faults are detected and cleared with a complete blackout of the microgrid, without selectivity. This level could be used for island mode for some combinations of operating generators.

Due to economic constraints, it may not be possible to ensure the high level (full selectivity) in all possible operating modes. The cost of the protection system could be too expensive to achieve the targeted availability. The protection system could be based on the three levels described above, but these levels shall be clearly identified during the protection system design.

4.3.5 Operating time (speed) of protection

The maximum clearing time of the protection system shall be determined according to the following requirements:

- a) Maximum short-circuit clearing time to ensure stability of the microgrid (depending on the behaviour of generators during short-circuits; three-phase faults could be the most onerous disturbances).
- b) The equipment's ability to withstand the through fault current due to an external fault for the maximum fault clearance time.
- c) The thermal withstands (managed by thermal overload protection, without any new challenge in microgrids in comparison with conventional grids).
- d) Step and touch voltage requirements, defined by current versus time curves defined in local regulations and international standards.
- e) Time selectivity with loss of main protection settings defined by FRT requirements: for short-circuits inside the microgrid or the main grid, a voltage sag can occur, with a risk of unwanted operation of loss of mains protection. The short-circuit protection and the loss of mains protection shall be coordinated to avoid a false opening of the POC. The short-circuit protection shall clear the fault inside the main grid or inside the microgrid before the operating time of the loss of mains protection elapses.

4.4 Particular requirements for non-isolated microgrids

The specific challenge for protection systems of non-isolated microgrids that can operate in island and grid-connected modes is to manage the significantly different conditions in the two operating modes.

- a) In grid-connected mode:
 - The short-circuit current is generally higher than in island mode, so it is easier to detect. However, all the protection inside the microgrid shall remain stable in case of faults in the grid. In the case of a short-circuit inside the microgrid, the protection system should isolate only the faulted part instead of isolating the entire microgrid, in order to maximize the availability of supply (selectivity issue).
 - The loss of mains protection shall disconnect the microgrid from the main grid only if the fault is located on the feeder from the main grid which supplies the microgrid. The loss of mains protection shall remain stable if the fault is located in the microgrid (fault shall be cleared by microgrid protection) or located on adjacent feeders of the main grid (fault shall be cleared by main grid protection). If the POC protection is not stable, the microgrid will be islanded when there is a fault on an adjacent feeder inside the main grid or inside the microgrid.
- b) In island mode, the protection system should be able to manage the following changes:
 - When the earthing system in island mode is different from the earthing system in grid-connected mode, earth fault protection settings and selectivity shall be suitable for the different locations of earth fault current source.
 - When the short-circuit current in island mode is significantly lower than in grid-connected mode, protection schemes used for grid-connected mode might not be sensitive enough

for island mode. Specific protection could be required, in addition to conventional overcurrent functions used for the grid-connected mode.

- The opening of the POC can modify the selectivity rules between protection inside the microgrid.
- c) The management of grid-connected or island modes can require a setting change to ensure detection and selectivity in each mode. These adaptive settings can be managed in a number of different ways. The most prevalent is by the selection of group setting features commonly available in multifunctional relays.
- d) Fault ride-through (FRT) capability of generators in a microgrid should be considered during the protection design phase. Generators need to meet the grid connection requirements of the local network operator if the microgrid can be operated in grid-connected mode. The FRT requirements include the voltage against time curve associated with the grid characteristics, pre-fault conditions, current injection (active/reactive current priority, sequence components, response behaviour) and post-fault behaviour. The settings of the protection systems should refer to the FRT settings to ensure the generators are not tripped before the network protection, especially during the islanding operation.

4.5 Particular requirements for isolated microgrids

Protection systems for isolated microgrids are simpler than for non-isolated microgrids, because the grid-connected mode is not applicable. However, all the requirements defined in 4.3 shall be fulfilled. The main challenge is the possible low short-circuit current magnitudes in some operating modes.

The short-circuit current magnitude and characteristics of an isolated microgrid should be considered during the design phase. In an isolated microgrid, there shall be at least one grid-forming generator in the system that provides the main source of short-circuit current. The other sources can be controlled as grid-following or grid-supporting devices that provide normal FRT behaviour.

5 Protection systems for microgrids

5.1 General

Protection systems for microgrids could be based on two basic approaches.

- a) Stand-alone de-centralized protection based on local measurements (e.g. current, voltage) with selectivity based on different principles:
 - Time selectivity, which remains applicable for some parts of the microgrids close to terminal feeders, or simple microgrid architectures where all sources are located on the same busbar and not distributed on several busbars.
 - Logic selectivity, with or without signalling schemes (e.g. directional blocking schemes).
 - Zone selectivity of unit protection (e.g. differential protection), based on CT locations.
- b) Centralized protection based on measuring devices associated with specific circuit-breakers in the microgrid. These measuring devices send raw or pre-processed data (e.g. sampled values or phasor values of currents or voltages, binary information such as switch position or current flow direction) to centralized equipment in real time remote via a communications link. Based on all these synchronized data, the centralized protection can locate the fault and trip the relevant circuit-breaker(s) to ensure selective fault clearance.

In the case of centralized protection, the local measurements can be processed to determine local protection criteria (as backup protection), i.e. combinations of local stand-alone protection and centralized protection are feasible and recommended.

This document is not intended to provide a complete description of all possible protection functions and applications in a microgrid. It focusses on the most important and commonly applied protection functions, where application in microgrids might require special attention.

It neither goes into details of what kind of signal quantity is monitored (e.g. measured phase current or calculated sequence current, true RMS value or fundamental component) nor how the measured value is evaluated (window length or number of samples, filtering methods, etc.). Due to the wide range of solutions available among the different products, the protection engineer remains responsible for choosing the appropriate function and solution for the application.

Apart from those protection functions listed in this document, many other protection functions exist for specific applications (such as earth fault protection in systems with no effective earthing) or specific types of equipment protection (such as overload protection or generator protection). However, these do not depend on whether the protected equipment is within a microgrid or a conventional power system.

To meet the reliability and selectivity requirements of protection systems defined in Clause 4, the following are some general design recommendations for microgrid protection systems:

- 1) More than one protection level to enhance fault detection and selectivity should be used.
- 2) Communication among the protective relays should be used whenever possible, for better coordination. It can be used to manage setting adaptation according to the operating mode (grid-connected or island mode) or used to manage a centralized protection system (with a back-up level based on stand-alone protection functions, not reliant on communication links).
- 3) Differential and directional protection functions should be considered whenever economically viable, as they are well suited to power systems with distributed generators.

5.2 Short-circuit protection

5.2.1 Overcurrent protection

5.2.1.1 Application of overcurrent protection in microgrid

Simple overcurrent protection is generally only applicable in the case of unidirectional short-circuit current flow.

5.2.1.2 Phase overcurrent protection

Phase overcurrent protection functions are described in IEC 60255-151 (IEEE/ANSI C37.2/ANSI function number 50/51).

This protection can be used for grid-connected mode, as it is well suited to detect high short-circuit current which are generally provided by the main grid.

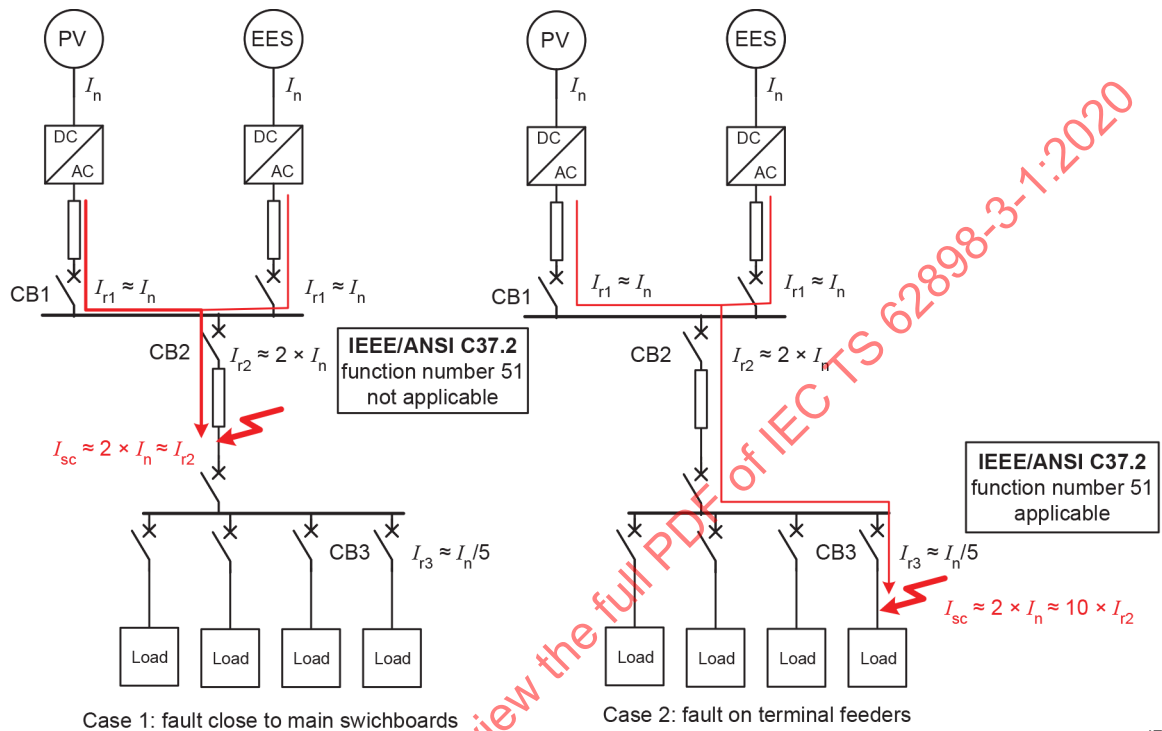
This protection is not applicable in locations with low short-circuit currents close to rated value, for example feeders located between busbars connected to distributed generators (Case 1 in Figure 1). However, this protection can be used on final circuits directly supplying only loads, where the ratio between the minimum short-circuit current and the maximum rated current is high enough to be able to define an overcurrent setting (Case 2 in Figure 1). These final circuits close to loads are generally unidirectional (single infeed). Phase overcurrent can be set with time selectivity with upstream protection. Such overcurrent protection embedded in LV miniature circuit-breakers (MCBs) or LV moulded-case circuit-breakers (MCCBs) remains applicable for LV terminal panels.

Figure 1 gives a simplified example to illustrate the impact of the ratio between the minimum short-circuit current and the maximum load current, where

I_n is the nominal/rated current of converter-based-generator (same value assumed for both generators to simplify the figure);

I_{sc} is the minimum short-circuit current of the converter-based-generator (in steady state). It could be close to the generator nominal value;

I_r is the current setting of each circuit-breaker, equal to or above the maximum load current.



IEC

Figure 1 – Ratio between maximum load current/minimum short-circuit current in the microgrid

In Case 1, the short-circuit current is approximately equal to two times the nominal current of each generator. This short-circuit level remains very close to the maximum load current which is seen by CB2. It is not possible to define a setting for CB2 below the minimum short-circuit current I_{sc} and above the maximum load current I_{r2} .

In Case 2, the short-circuit current is nearly the same as Case 1 (line/cable/fault impedances are neglected) but the short-circuit current is higher than the maximum load current seen by CB3. The current setting of CB3 is lower than CB2 because the maximum load current is lower (1/10 ratio in the figure). In this case, it is possible to define a setting below the minimum short-circuit current I_{sc} and above the maximum load current I_{r3} .

5.2.1.3 Earth fault protection

Earth fault protection is a protection intended to operate for power system earth faults. Earth fault protection functions are described in IEC 60255-151 (IEEE/ANSI C37.2 function number 50N/51N).

This protection is applicable in microgrids with a single earthing system (hence unidirectional earth fault current) with the same constraints as in conventional systems. If there are several neutral-to-earth connections at different locations, simple earth fault protection is generally replaced by directional earth fault protection or other more complex protection functions to ensure selectivity.

Time selectivity between different 51N stages can be used when there is a single earthing system. In this case, the earth fault short-circuit current is unidirectional and simple time discrimination is possible. If the system is based on multiple earthing points, use of earth fault overcurrent alone cannot guarantee fault protection's selectivity. Hence, directional earth fault protection could be required to ensure selectivity.

Sensitive earth fault protection could be required for low (limited) earth fault short-circuit currents. For MV feeders, such sensitivity is generally achieved by the use of a sensitive 51N relay connected to a core balance current transformer. For LV feeders, a residual current device (RCD) or ground fault protection can be used.

5.2.1.4 Voltage-controlled overcurrent protection

Voltage-controlled overcurrent protection functions are described in IEC 60255-151 (IEEE/ANSI C37.2 function number 51V).

With conventional grids or microgrids supplied by synchronous machines, the voltage-controlled overcurrent protection function is used as backup protection function to secure phase-fault clearing. This function is generally included with all the generator protections. This function can detect low short-circuit currents, delivered by synchronous machine with or without over-excitation (with a steady state short-circuit current below the rated value).

With microgrids based on a high proportion of converter-based generators, voltage-controlled overcurrent could be used as the main protection function to detect low short-circuit currents. The discrimination between low short-circuit current and normal load current is based on voltage levels (e.g. the minimum of the three phase-to-phase or the three phase-to-neutral voltages). With normal load current, the voltage remains close to the rated value (normally between 0,9 and 1,1 times the nominal value). In the event of a short-circuit, the voltage is determined by the fault location and the impedance between the short-circuit and sources. Depending on the fault impedance, the voltage can drop below 50 % of the nominal value.

In microgrids, voltage-controlled overcurrent can be used at different locations inside the microgrid, based on time or logic discrimination. For distributed generators with bidirectional short-circuit currents, voltage-controlled overcurrent protection can be associated with a phase directional element.

5.2.1.5 Fuse

A fuse is one type of overcurrent protection device rather than a "protection function". It operates by melting of the fuse-element when the current exceeds a given value for a sufficient time.

For microgrids, fuses have the same application constraints as for overcurrent protection (function number 51). Fuses have an inherent inverse-time characteristic, i.e. the operation time depends inversely on the current. Fuses are thus not well suited for cases of low short-circuit current close to the rated value (typically in island mode).

5.2.2 Directional overcurrent protection

5.2.2.1 Directional phase overcurrent protection

Directional phase overcurrent protection functions are described in IEC 60255-12 (IEEE/ANSI C37.2 function number 67).

This protection is typically used to ensure selectivity in systems with distributed energy resources and bidirectional short-circuit current flows, for example closed ring with single infeed.

Selectivity can be ensured with time selectivity or logic selectivity (signalling schemes).

The phase directional element can be logically combined with voltage-controlled overcurrent. Voltage-controlled overcurrent ensures detection of the short-circuit path and the directional element enables time selectivity between protection stages or a directional logic selectivity.

5.2.2.2 Directional earth fault (residual) protection

Directional earth fault protection functions are described in IEC 60255-12 (IEEE/ANSI C37.2 function number 67N).

This protection is applicable to earth fault detection, depending on the selected earthing system.

With distribution grids and long feeders, this protection can be required to distinguish between the capacitive current of a healthy feeder and fault current in a faulted feeder. This is particularly the case for systems with limited earth fault current, such as isolated neutral, impedance earthed or resonant earthed neutral (Petersen coil) earthing systems.

Specific directional earth fault protection is required to detect restriking faults. Fault detection is based on transient signal analysis, and the protection shall be able to distinguish the transient signal in the faulted feeder from the transient signals which also occur on healthy feeders.

5.2.3 Distance protection

Distance protection functions are described in IEC 60255-121 (IEEE/ANSI C37.2 function number 21).

This protection is applicable to any system architecture, only limited by minimum sensitivity (minimum fault current) and minimum zone size.

Distance protection is applicable as a main protection function to MV feeders (lines, cables) with time selectivity (if feeder impedance is high enough to set up selective zones, otherwise using signalling schemes) and to busbars with logic selectivity (signalling schemes).

5.2.4 Directional power protection

Directional power protection functions are described in IEC 60255-12 (IEEE/ANSI C37.2 function number 32).

This protection is applicable to protect generators from running as a motor (using reverse active power as the criterion) when excessive power from distributed generators is injected into a synchronous machine (e.g. PV without curtailment).

5.2.5 Differential protection

Differential protection functions are described in the following parts of the IEC 60255-187 series:

- a) IEC 60255-187-1 for transformer, motor and generator differential protection (IEEE/ANSI C37.2 function numbers 87T, 87M, 87N and 87G);
- b) IEC 60255-187-2 for busbar differential protection (IEEE/ANSI C37.2 function number 87B);
- c) IEC 60255-187-3 for line differential protection (IEEE/ANSI C37.2 function number 87L).

This protection is applicable to MV microgrids irrespective of whether in grid-connected or island mode, i.e. there is no need to adjust settings in the case of a change in grid connection.

The protection is applicable to all types of equipment (cable, line, busbar, transformer, generator, motor) but may not be cost-effective if new communication links are required.

This protection may not provide sufficient sensitivity for earth fault detection in systems with limited earth fault current (not solidly earthed neutral). In this case, additional sensitive earth protection shall be added to ensure a complete protection system (e.g. 51N or 67N).

Differential protection cannot provide backup protection for faults on adjacent equipment.

5.3 System protection

5.3.1 Under/over voltage protection

5.3.1.1 Phase undervoltage protection

Phase undervoltage protection functions are described in IEC 60255-127 (IEEE/ANSI C37.2 function number 27).

This protection is typically used as backup protection, to trip generators in case of excessively long low voltage conditions (fault not cleared by feeder protection).

This protection can be used on all busbars where generators are connected, with a simple time selectivity to all feeder protection.

Phase undervoltage protection is also useful in addition to the internal protection embedded in converter-based-generator control systems.

Phase undervoltage function is generally required in the loss of mains protection at the POC, to detect fault situations in the main grid (for grid-connected microgrids). In this case, selectivity shall be ensured with all the protection inside the microgrid, to avoid false disconnection from the main grid in the event of a fault inside the microgrid. The phase undervoltage protection at the POC shall meet the FRT requirements, if any.

5.3.1.2 Phase overvoltage protection

Phase overvoltage protection functions are described in IEC 60255-127 (IEEE/ANSI C37.2 function number 59).

This protection is typically used as backup protection, for example to trip generators in case of failure of voltage control.

This protection can be used on all busbars where generators are connected.

Phase overvoltage function is generally required in the loss of mains protection at the POC, to detect fault situations in the main grid (for grid-connected microgrids). The phase overvoltage protection at the POC shall meet the FRT requirements, if any.

5.3.1.3 Residual overvoltage protection

Residual overvoltage protection functions are described in IEC 60255-127 (IEEE/ANSI C37.2 function number 59N).

This protection is typically used as backup protection for earth faults not cleared by the main feeder protection. It can also be a main protection in microgrids with isolated neutral or high impedance earthed systems.

This protection can also be used to provide an alarm in the event of an earth fault in an isolated neutral or resonant earthed neutral system without automatic disconnection of supply (in addition to an insulation monitoring device, if any).

Residual overvoltage protection can be used as a part of the loss of mains protection at the POC of a microgrid with an MV connection to the main grid. In this case, selectivity shall be ensured with all the earth fault protection inside the microgrid to avoid false disconnection from the main grid in the event of a fault inside the microgrid. The residual overvoltage protection at the POC shall meet the FRT requirements, if any.

5.3.2 Frequency protection

Frequency protection functions are described in IEC 60255-181 and include three types:

- a) underfrequency (IEEE/ANSI C37.2 function number 81U);
- b) overfrequency (IEEE/ANSI C37.2 function number 81O);
- c) rate of change of frequency (ROCOF) (IEEE/ANSI C37.2 function number 81R).

This protection is used to detect an unstable situation in power systems, for example in the event of an unbalance between load and generation. Frequency protection has classically been implemented through underfrequency load shedding schemes but can also be applied as overfrequency generation shedding in microgrids.

Frequency protection is generally required in the loss of mains protection at the POC, in association with ROCOF, for underfrequency thresholds close to nominal frequency. Frequency protection at the POC shall meet the frequency ride-through requirements, if any.

5.4 Centralized protection systems

Centralized protection of a microgrid needs to integrate all information into a computer-based fault protection system to protect all parts of the microgrid, or subparts of the microgrid in combination with stand-alone protection devices.

Centralized protection employs a variety of sensors and a combination of software and hardware in order to acquire a wide range of information about the system. It is based on protection functions that are easy to coordinate in a centralized system. Centralized protection mainly integrates protection functions in the microgrid to improve the overall performance of the protection.

A centralized protection system of a microgrid consists of the following parts:

- a) Measurement units: A wide variety of sensor types can be employed to measure the required system parameters at different locations within the microgrid.
- b) Communications network: A communications medium is needed in a centralized protection network. A redundant structure may be used to increase reliability. For example, the IEC 61850 communications protocol can be used to provide interoperability and applicable semantic data models describing microgrids.
- c) Central protection unit: The measured data of a variety of parameters from different parts of the system is received, and the information is exchanged between the central protection unit and either measurement units or switching devices or both through the communication network.

Centralized protection can be based on overcurrent protection, differential protection, other protection types or their combination. Centralized protection typically involves measurement of current on each branch and voltage at each busbar in the microgrid. Centralized protection is based on advanced and detailed information and hence requires a fast and reliable communications medium and protocol.

As centralized protection is based on communications links which could fail, backup protection shall be included to ensure fault clearing in all cases. The backup protection could utilize, for example, time coordination with the centralized system.

6 Dynamic stability and control

6.1 General

The nature of the stability and dynamic performance of a microgrid is different from that of a conventional power system. Special features of a microgrid related to its size, system inertia and the type of generators used result in the need for special consideration for stability and control of microgrids. Another factor is the low X/R ratios of distribution lines in microgrids, as a result of which there is a strong coupling between active and reactive power and hence between voltage and frequency. Thus, any disturbance in a microgrid can be manifested in all system variables.

For a microgrid operating in island mode, fault incidents (occurrences and clearances) or fluctuations of large loads or DER power output can cause severe disturbances. Such disturbances should be accurately distinguished from faults. The initial characteristics of faults and other disturbances are similar. For other disturbances, the fault detection signals will return to their normal values quickly due to the actions of the transient and dynamic control systems of the microgrid. For faults, the detection signals remain significantly different from their normal values for a longer period and this results in tripping of appropriate circuit-breakers. Dynamic and transient controls against disturbances play a key role in microgrid operational reliability.

6.2 Dynamic stability in microgrids

6.2.1 General

Stability of microgrids is critically different from stability of the conventional grid due to factors such as:

- a) smaller size;
- b) short feeder lengths and low X/R ratios;
- c) higher proportion of intermittent renewable energy resources;
- d) existence and (in some cases) dominance of converter-based generators;
- e) low system inertia;
- f) different modes of operation (grid-connected and island modes);
- g) susceptibility to unbalanced (between phases) operation.

These issues are prevalent in island mode of operation or in isolated microgrids. In the case of grid-connected operation, the task of stabilizing the system voltage and frequency lies with the interconnected grid and hence less is required from the control functions which contribute to the dynamic stability.

Stability issues in microgrids can be due to control system stability or power balance stability. The control systems of electric machines or of CBGs can be a possible source of stability issues in microgrids. These issues are related to inadequate control schemes or poor tuning of equipment controllers. Effective load sharing among the generating units of a microgrid is also critical to ensure stable operation. Stability issues related to power balance are associated with the following events:

- 1) loss of a generation unit;
- 2) violation of DER power limits;
- 3) poor load sharing among DER;
- 4) wrong choice of the grid-forming generator;
- 5) unplanned load switching.

Microgrids shall have the capability to regain steady state so that the system state variables stay within admissible operating ranges after being subjected to such disturbances. The stability requirements can be expressed in terms of the magnitude, angle or frequency of the voltage.

Voltage instability and frequency instability are common phenomena and are handled independently in conventional large grids. In microgrids, voltage and frequency can be strongly coupled due to the low X/R ratio of feeders and hence the classification in this conventional approach is less useful. Two types of stability, transient stability and dynamic stability, are thus defined to better characterize the stability issues that are faced in microgrids. Transient disturbance control is needed to achieve transient stability. Similarly, dynamic disturbance control is needed to achieve dynamic stability.

6.2.2 Disturbances in microgrids

6.2.2.1 Transient disturbances

Transient disturbances in microgrids correspond to the following events:

- a) unintentional mode transfer of microgrids between grid-connected and island modes;
- b) heavy load on/off switching;
- c) major DER on/off switching;
- d) fault clearing.

Transient disturbances are related to the so-called "large disturbances" which are characterized by large frequency and voltage excursions and power swings among multiple DER as well as short time periods (usually in the order of 0 ms to about 50 ms).

6.2.2.2 Dynamic disturbances

Dynamic disturbances are related to the following situations:

- a) the output of renewable energy sources in a microgrid reaches a sufficiently high proportion that the system approaches its stability boundary;
- b) planned islanding of a microgrid with a large number of non-linear loads;
- c) intermittency, uncertainty and output power fluctuation of renewable energy resources;
- d) non-linear loads having harmful effects on power quality beyond what is acceptable under local regulations;
- e) grid-side faults causing abnormal conditions of microgrids due to FRT requirements.

The time frame involved in dynamic disturbances is longer than that of transient disturbances (usually in the order of about 50 ms to 2 s). Dynamic disturbance issues commonly refer to sustained, lightly damped oscillations following a disturbance of small magnitude.

6.2.3 Voltage and frequency stability

6.2.3.1 Voltage stability

As microgrids involve short LV and MV lines rather than long transmission lines, voltage stability issues related to voltage drops between the ends of feeders, and slow and sustained decay of voltage, are not prevalent in microgrids. Voltage stability in microgrids is rather related to the limits of DER, voltage sensitivity of loads and to poor reactive power sharing among DER. Voltage stability issues in microgrids may be expressed in the form of undamped voltage oscillations, low or high steady-state voltages (under- or over-voltage), large power swings, DC link voltage ripples, or pole slipping in machines.

In order to ensure voltage stability in microgrids, the following considerations shall be taken into account:

- a) Boundary conditions shall be properly set for the output powers of the DER (in a centralized control system) to make sure that the power limits of the DER are neither surpassed nor approach the point where undamped voltage ripples may be caused.

- b) The voltage-reactive power droop slopes shall be correctly selected in DER implementing droop control.
- c) Reactive power demand shall be shared appropriately among the DER.
- d) Special requirements of loads with high sensitivity to voltage stability shall be taken into consideration.
- e) The capacity of EES systems shall consider voltage stability requirements and EES size relative to the overall microgrid system size.

6.2.3.2 Frequency stability

Frequency stability issues are a major concern in island mode of operation and in isolated microgrids, due to the characteristically low system inertia and high proportion of intermittent renewable DER. The low X/R ratios of microgrid feeders, resulting in strong coupling between voltage and frequency, is also another issue worsening the frequency stabilization in microgrids. Due to the strong coupling between voltage and frequency in microgrids, frequency and voltage changes are also reflected as variations of load power. The microgrid system frequency control shall be coordinated with the primary control of DGs and voltage and frequency dependence of system loads. The generation units involved in microgrids are typically small in size and number, compared to interconnected grid, which means disconnection of one of the units could cause large changes in the system frequency with a high rate of change. Conventional frequency control techniques may not be fast and capable enough to address these challenges. Hence, specially designed frequency control should be available in order to ensure frequency stability in microgrids operating in island mode.

6.3 Dynamic control in microgrids

6.3.1 General requirements

To achieve stability in microgrids, dynamic control for microgrids shall meet the following requirements:

- a) Selectivity: the control action to be taken in response to a disturbance should be selected to minimize the impact on normal system conditions and avoid unnecessary reduction or loss of power supply from the DGs.
- b) Speed: control actions should be taken fast enough that the microgrid can recover its stable operational status after a disturbance.
- c) Reliability: the microgrid stability control should operate without failure, when required and should not operate when action is not required.
- d) Accuracy: the generated power to be reduced or increased through EESs, or the load to be changed due to the stability control action, should be of the right amount and applied at the right time.
- e) Adaptability: the decision criteria and control actions should be adjustable based on the mode of operation of the microgrid (grid-connected or island) and the status of the DER and loads in the microgrid.
- f) Coordination: For a central control system there should be proper coordination between the central controller and the local controllers of the DER and the load management, so that undesirable control actions are avoided.

6.3.2 Dynamic control functions

Stability control in microgrids is used to achieve the following functions:

- a) maintaining the system in stable conditions that satisfy the operational constraints, such as acceptable ranges of voltage and frequency;
- b) avoiding interaction between CBGs and preventing undamped oscillations in the system following small disturbances;

- c) preventing abnormal conditions or system collapse during disturbances such as load changes, DER power changes, occurrence and clearance of faults, component failures, operational setpoint adjustments or transition between operation modes;
- d) avoiding serious consequences such as blackout and system collapse from undesired operation of the microgrid;
- e) restoring all state variables to new steady-state values which satisfy operational constraints after being affected by a disturbance;
- f) enabling the microgrid to black start in case of system failure;
- g) ensuring microgrid resynchronization with the main grid;
- h) making sure that critical loads are supplied without interruption.

6.3.3 Control elements in microgrids

6.3.3.1 Major control elements in microgrid

Control systems of microgrids involve

- a) multilevel control functions implemented through a central controller for overall stable system operation, and
- b) individual local control units for control of power outputs and consumption of generation units and loads.

Microgrids may include the following elements that can be involved in the dynamic control of the microgrids (see Figure 2):

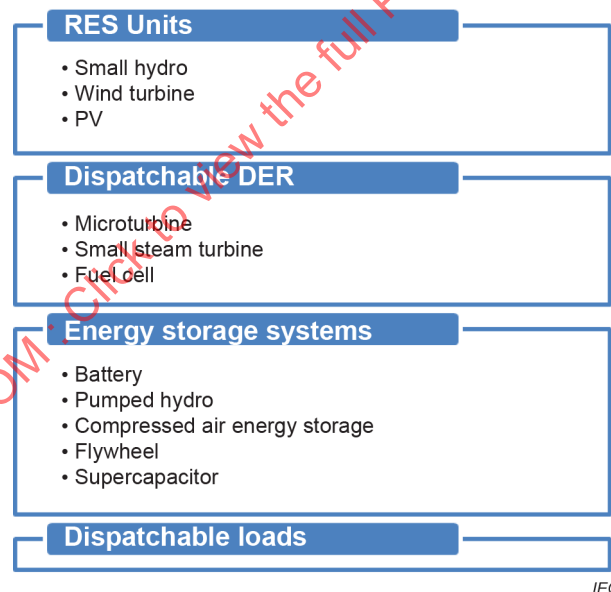


Figure 2 – Control elements in microgrids

6.3.3.2 Intermittent RES units

Intermittent RES units are very common in microgrids and in some cases the dominant sources of power supply. Controllability of these units is limited by the physical nature of the primary energy resource, which mostly are non-dispatchable. However, there is the possibility to control the reactive power output from RES units, independently from the available active power, through properly designed power electronic interfaces. Thus, RES units with independent reactive power interfaces can be employed in reactive power control for system stability in microgrids.

Some wind turbines and small hydroelectric power units may use constant speed induction generators which may not need converter interfaces. In such units, the mechanical power output determines the generated active power. Shunt compensators may be used to control the reactive power. Variable speed wind turbines, however, involve converters. There may be two converters in some cases. The source side converters are usually voltage source inverters and are controlled to provide maximum power point tracking capability. The grid side converters are controlled for DC link voltage regulation and control of active and reactive power output.

PV systems also involve inverters which allow control of the active and reactive power output of the system. Maximum power point tracking (MPPT) control is an important aspect in PV systems and may be achieved through either the DC-AC inverter or a DC-DC buck-boost converter.

6.3.3.3 Dispatchable DER

Dispatchable or quasi-dispatchable units that generate power in proportion to their fuel consumption may also exist in microgrids. This fuel dependency provides controllability of the unit and allows flexibility of the output (both active and reactive power outputs). Thus, dispatchable sources are the main source of controllability in microgrids. Choosing DER with fast unit response time (high ramp rate) is advantageous to ensure stable operation of microgrids.

6.3.3.4 Energy storage systems

Energy storage systems are important for stable operation of isolated microgrids or island mode of non-isolated microgrids. The EESs may be suited to either energy intensive or power intensive applications based on their response rate and storage capacity. These EESs can serve as controllable AC voltage sources to ensure voltage and frequency stability in microgrids.

Energy storage systems for power intensive applications, such as fly wheels and supercapacitors, can be used for transient disturbance control of microgrids. Energy storage systems for energy intensive applications, such as batteries and pumped storage, can be used for dynamic disturbance control of microgrids. Examples of such applications of EESs for transient and dynamic disturbance controls are given in Annex A.

6.3.3.5 Dispatchable loads

Controllable and interruptible loads in microgrids can serve as controllable components that can contribute to frequency and voltage stabilization. Their active power consumption can be controlled based on the system frequency and voltage.

The detailed requirements for methods of implementing this technique are specified in IEC TS 62898-3-3¹.

6.3.4 Control systems of microgrids

6.3.4.1 Control system hierarchy

Control systems of microgrids, especially those with a sufficiently high number of components, involve a hierarchy of control functions. See Figure 3.

¹ Under consideration. Currently at CDM stage.

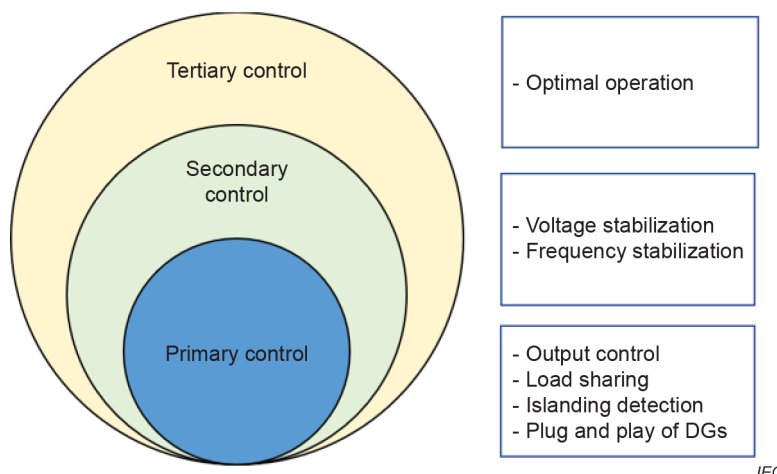


Figure 3 – Hierarchical control levels of a microgrid

Primary control includes fundamental control hardware for internal voltage and current control loops of the DER. Secondary control is intended to compensate for deviations in the system-level voltage and frequency which are caused by the primary controls, through which voltage and frequency stability can be ensured. Higher level controls, such as optimal operation (for optimization of parameters such as cost, power loss, emission) and power exchange with the grid, generally operate over longer times and are handled by the tertiary control. Detailed requirements for tertiary control and its functions are provided in IEC TS 62898-3-22.

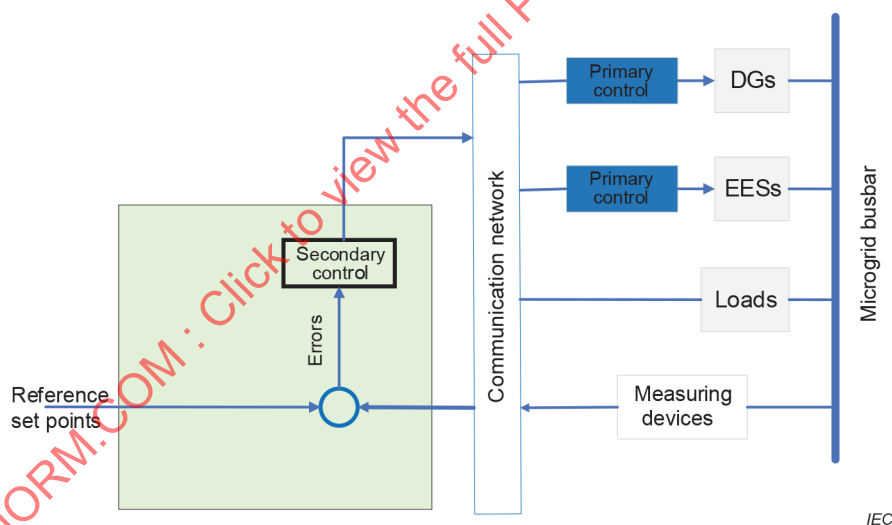


Figure 4 – Centralized multilevel control of microgrids

A typical centralized multilevel control for a microgrid is shown in Figure 4. In island mode, the reference set points are the nominal voltage and frequency. In grid-connected mode the DG operate in PQ control mode and hence the reference set points are the active and reactive power. The microgrid central controller encompasses the secondary control and has overall control of the multilevel control system. It communicates regularly with the local DGs or load controllers and manages the operation of the microgrid by providing set points to the local controllers.

² Under consideration. Currently at CDM stage.

6.3.4.2 Primary control

Primary control of microgrids is exclusively based on local measurements, local calculations and local implementation. Hence, it does not require a communications network. Primary control carries out functions such as output control, load sharing, islanding detection and plug and play of DGs. Synchronous generators achieve functions of power sharing and output control through their governor, voltage regulator and the machine inertia.

Microgrids dominated by CBGs have very low or no inertia compared to conventional grids or microgrids involving conventional synchronous machines. The primary control in such microgrids is achieved through control of the interfacing voltage source converters. Different types of CBGs employ different primary control methods to achieve primary control functions.

- a) Grid-forming CBG: The primary control in grid-forming CBGs is intended to provide functions such as voltage stability, frequency stability, black start capability and load sharing. Grid-forming CBGs are voltage sources that provide voltage and frequency references for the microgrid in island mode of operation. Control strategies including droop control, virtual synchronous machine control, AC voltage control, AC current control, indirect current control and active current sharing can be used for primary control of grid-forming CBGs.
- b) Grid-supporting CBG: Grid-supporting CBGs are controlled current sources or controlled voltage sources with control functions such as maximizing active power output and supporting reactive power. MPPT control and AC voltage control are some of the common primary control strategies in grid-supporting CBGs.
- c) Grid-following CBG: The voltage and frequency of grid-following CBGs are imposed by the main grid in grid-connected mode or a grid-forming CBG in island mode. Hence, grid-following CBGs are current sources with the intention to inject a pre-defined level of active and/or reactive power so as to provide functions such as power dispatch and real and reactive power support. Control strategies for primary control of grid-following CBGs include current control, AC voltage control, virtual oscillator based control, virtual flux oriented control and direct power control.

Power sharing is one of the critical functions of primary control. The most widely used methods for implementation of this function are droop based methods. Conventional droop control is based on the relationships expressed by Formulae (1) and (2).

$$f_{\text{ref}} = f_0' - K_P (P - P_0) \quad (1)$$

$$U_{\text{ref}} = U_0' - K_Q (Q - Q_0) \quad (2)$$

where

- f_{ref} is the reference frequency;
- f_0' is the fundamental system frequency;
- K_P is the active power regulation coefficient;
- P is the measured active power;
- P_0 is the pre-set reference power;
- U_{ref} is the reference voltage;
- U_0' is the targeted system voltage;
- K_Q is the reactive power regulation coefficient.

Improved versions may be used for better performance of droop control when adopted for microgrid where there is higher coupling of active and reactive power. In case of grid-connected operation mode, the grid code requirements for acceptable primary control band, frequency

active power droop characteristics and voltage reactive power droop characteristics shall be satisfied.

6.3.4.3 Secondary controls

Secondary controls are centralized controls and the second layer control in a hierarchical control of the microgrid. They are designed with slower dynamic response relative to primary control. Secondary control complements the task of the primary control to improve the power quality and system performance of the microgrid. It is intended to restore the frequency and voltage amplitude by compensating for the impact of the primary control on steady state characteristics.

As shown in Figure 4, frequency and voltage magnitude at the microgrid main busbar are compared against the corresponding reference values. The error signals of voltage and frequency are processed to calculate the control signals for the primary controllers of the DGs to compensate for the frequency and voltage deviations. This relation is expressed in Formulae (3) and (4).

$$\delta f = K_{p,f} (f_{ref} - f) + K_{i,f} \int (f_{ref} - f) dt + \Delta f_s \quad (3)$$

$$\delta U = K_{p,U} (U_{ref} - U) + K_{i,U} \int (U_{ref} - U) dt \quad (4)$$

where

δf is the error in frequency;

$K_{p,f}$ is the power to frequency regulation proportional coefficient;

f_{ref} is the reference frequency;

f is the measured frequency;

$K_{i,f}$ is the power to frequency regulation integral coefficient;

t is the time;

Δf_s is the error in system frequency ;

δU is the error in voltage;

$K_{p,U}$ is the power to voltage regulation proportional coefficient;

U_{ref} is the reference voltage;

U is the measured voltage;

$K_{i,U}$ is the power to voltage regulation integral coefficient. Secondary controls may also cover control for parallel operation performance of generators. Some of the control techniques for parallel operation of multiple generators are:

- Master-slave control: A voltage-controlled inverter is used as a master unit which maintains the output voltage magnitude and frequency. This converter generates current commands to the current-controlled inverters, which are the slave units.
- Power sharing control: The current from each unit is measured and compared to the calculated average value to generate the control signal for load sharing.
- Generalized droop control: This control technique uses either conventional frequency/voltage droop control, opposite frequency/voltage droop control, or their combination with other techniques.

Secondary control may also be able to provide ancillary services such as those stated in IEEE Standard 1547, for example load regulation, spinning reserve, voltage regulation, and reactive power supply.