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IEEE Standard for the Specification of Microgrid Controllers

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IEEE Standard for the Specification of Microgrid Controllers

Sponsor

Transmission and Distribution Committee
of the
IEEE Power and Energy Society

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IEEE-SA Standards Board

Abstract: A key element of microgrid operation is the microgrid energy management system (MEMS). It includes the control functions that define the microgrid as a system that can manage itself, operate autonomously or grid connected, and seamlessly connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services. The scope of this standard is to address the functions above the component control level associated with the proper operation of the MEMS that are common to all microgrids, regardless of topology, configuration, or jurisdiction. Testing procedures are addressed.

Keywords: distributed energy resources, distributed energy storage, distributed generation, electric distribution systems, energy management system, IEEE 2030.7™, interconnection agreement and requirements, islanding, microgrid, microgrid controller, power quality

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Introduction

This introduction is not part of IEEE Std 2030.7–2017, IEEE Standard for the Specification of Microgrid Controllers.

The technologies and operational concepts to properly integrate and manage microgrids interconnected with existing distribution systems are being deployed. However, to fully realize the benefits and to avoid negative impacts on system reliability, there is a critical need to have a single document of standard technical requirements for microgrid controllers. This standard addresses this need by providing uniform criteria and requirements relevant to the performance and operation of the microgrid controller at the point of the interconnection.

The intent of this standard is to define the functional requirements of the microgrid controller in a manner that can be universally adopted. The universality relates to the technical aspects, while providing a common language for a wide range of stakeholders, e.g., vendors, utilities, energy service companies, developers, codes and standards organizations, regulators and legislators, and governing bodies.

This standard established the criteria and requirements for the microgrid controller at the point of interconnection. It is not a design or application guideline. It provides the minimum functional technical requirements that are universally needed to assure a technically sound operation of the microgrid at the point of interconnection. Any additional requirements should not be implemented to the detriment of the functional technical requirements of this standard.

This standard defines the functional specification of a microgrid controller that shall be tested using IEEE P2030.8™ Draft Standard for Testing of Microgrid Controllers.

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IEEE Standard for the Specification of Microgrid Controllers

1. Overview

1.1 Scope

This standard provides technical specifications and requirements for microgrid controllers. Additionally, there are informative annexes covering the description of the microgrid, the establishment of the functional specification, the structure of the microgrid control functions, and a bibliography. These are for informative purposes only, and can be referred to, but they are not required to be used in conjunction with this standard.

A key element of microgrid operation is the microgrid energy management system (MEMS). It includes the control functions that define the microgrid as a system that can manage itself, operate autonomously or grid connected, and seamlessly connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services. The scope of this standard is to address the technical issues and challenges associated with the proper operation of the MEMS that are common to all microgrids, regardless of topology, configuration, or jurisdiction, and to present the control approaches required from the distribution system operator and the microgrid operator. Testing procedures are addressed. Scenarios and/or use cases for testing are identified in this standard for dispatch function and transition function respectively. These cases shall be tested according to IEEE P2030.8.[1]

1.2 Purpose

The reason for establishing a standard for the microgrid energy management system (MEMS) is to enable interoperability of the different controllers and components needed to operate the MEMS through cohesive and platform-independent interfaces. This approach will allow for flexibility and customization of components and control algorithms to be deployed without limiting potential functionality. Microgrid components and operational solutions exist in different configurations with different implementations. Regardless of whether equipment and software are commercial or custom, components should be interoperable and have interfaces that comply with functional standards defined by the MEMS. The standardization focuses on defining functions and interface configurations that allow modularity and interoperability. It deals with the microgrid controller operation, and defines those aspects that need to be standardized and those that can remain proprietary, while enabling the interoperability with various distributed energy resources (DER) interfaces and facilitating the wide adoption by vendors and utilities. The standard is functionality driven and focuses on a modular approach that enables potential future expansion and features.

[1]Numbers preceded by P are IEEE authorized standards projects that were not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining drafts, contact the IEEE.

1.3 Limitations

The functional requirements in this document are applicable to all ac microgrid controllers, regardless of configuration, and whether they are connected to a distribution network or islanded. Limitations include the following:

- This standard does not define the individual or aggregate capacity of loads or generation installed in the microgrid. It does not specify voltage levels at the point of connection of the microgrid to the distribution grid nor within the microgrid.
- This standard does not prescribe protection schemes deployed within the microgrid, including protection functions of individual components and assets, nor the protection coordination that may be required with the distribution grid protection schemes.
- This standard does not address planning, designing, and operating the microgrid. This topic is covered in IEEE Std 1547.4™.
- This standard does not address issues related to the power exchanges between the microgrid and the distribution network at the point of interconnection.
- This standard does not address communication systems and the hardware, software, and protocols associated with the implementation of these systems.
- The requirements of this standard apply to a microgrid that has a single point of interconnection with the distribution grid. It does not consider microgrid-to-microgrid use cases or a microgrid that breaks up in sections, with each section operating independently.

The requirements in this standard are functional and do not specify any particular equipment or equipment type, nor a specific microgrid hardware or software implementation. It does not address communication systems and the hardware, software, and protocols associated with the implementation of these systems.

2. Normative references

The following referenced document are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE P2030.8/D9, IEEE Draft Standard for Testing of Microgrid Controllers, August 2017.[2]

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[3]

distributed energy resources (DER): Sources and groups of sources of electric power that are not directly connected to the bulk power system; they include both generators and energy storage technologies capable of exporting power.

distribution management system (DMS): A collection of applications designed to monitor and control a distribution network efficiently and reliably.

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[3]*IEEE Standards Dictionary Online* subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

microgrid: A group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes.

microgrid control system: A system that includes the control functions that define the microgrid as a system that can manage itself, operate autonomously, and connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services; it includes the functions of the microgrid energy management system (MEMS); it is the microgrid controller if implemented in the form of a centralized system.

point of interconnection (POI): The electrical point at which the microgrid connects to, or disconnects from, the main distribution grid.

seamless transition: The connection and disconnection of a microgrid to and from the larger grid accomplished without voltage and frequency transients that exceed the specifications of the microgrid design and the interconnection requirements.

4. Context and microgrid structure

4.1 Functional features of a microgrid

A microgrid is a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to enable operation in both grid-connected or island modes.

For the purposes of this standard, a microgrid is considered to interact with the external grid at one point, the point of interconnection (POI). If there are a number of points of contact, only one of those will be controlled for the purposes of integrating the microgrid. The term *point of interconnection (POI)* is adopted in this standard instead of the commonly used *point of common coupling (PCC),* given that the term *PCC* is found in several guidelines and standards in different power system contexts and with different meanings.

Microgrids are characterized as having a microgrid control system capable of automatically integrating and coordinating generation, storage (if applicable), controllable loads, and the grid intertie equipment within the microgrid required to interact with the larger grid as an aggregated single system.

The microgrid elements and components include the following: a) equipment connecting the microgrid to the distribution system at the POI (disconnects and breakers); b) the microgrid control system, including the energy management system; c) local distribution system components: transformers, switchgear, capacitors; d) devices for the interconnection and interaction of microgrid elements (disconnects and breakers); e) physical devices: DER and loads within the microgrid boundaries. A description of the microgrid components is provided in A.2.

For the purposes of this standard, an electrical system, which DER and aggregated controllable loads, shall have three distinct characteristics to be considered a microgrid:

a) Clearly defined electrical boundaries

b) A control system to manage and dispatch resources as a single controllable entity

c) Installed generation capacity that exceeds the critical load; this allows the microgrid to be disconnected from the main grid, i.e., operate as an entity in islanded mode, and supply local loads

The implementation approach for the transition from grid-connected to islanded modes is left to the microgrid designer or operator. This standard recognizes that microgrids may be designed to utilize drop and pickup, or black start, for this transition. Black start is the ability of a microgrid, in the absence of a grid connection or operating self-generation, to start its own generation and sequentially reenergize as an island. Black start relies on another source of startup power, typically batteries or a similar source, to start a first generator. This standard recognizes that automatic black start is a possible approach to implementing transitions.

4.2 Microgrid control system

A microgrid control system includes the control functions that define the microgrid as a system that can manage itself, operate autonomously or grid connected, and connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services. It is the sole point of interface with any DER device, DER management system (DERMS), or energy management system (EMS). It should have both real-time control and energy management functions that operate in the following situations:

a) Operation in grid-connected and islanded modes
b) Automatic transition from grid-connected to islanded mode by providing a managed transition to islanded mode for microgrid loads during abnormal bulk power system conditions and planned interruptions of the system
c) Resynchronization and reconnection from islanded mode to grid-connected mode
d) Energy management to optimize both real and reactive power generation and consumption
e) Ancillary services provision, support of the grid, and participation in the energy market and/or utility system operation, as applicable

Since there are many possible configurations for microgrids depending upon location and purpose, the requirements and functions of the microgrid and microgrid control system will differ. For this reason, this standard focuses on the requirements and functions, applicable to a large range of microgrids and microgrid controllers, which are generic and commonly applicable.

A microgrid control system consists of software, hardware, or a combination of both, and can be physically implemented in a variety of ways, including centralized or distributed. In this standard, the term *microgrid control system* is therefore used in place of *microgrid controller*, in recognition of the fact that the control functions may be distributed in the microgrid components rather than centralized in one controller. The microgrid control system also includes the energy management system (EMS) functions required to dispatch microgrid resources. These functions are commonly used in commercial and industrial installations.

This standard specifies the core-level functions which any microgrid control system shall implement, and their minimum requirements.

4.3 General considerations and requirements

The operator of the distribution grid to which a microgrid interconnects has requirements which shall be met for the point of interconnection (POI) of the microgrid. These include technical requirements such as anti-islanding, low- or high-voltage and/or frequency ride-through, and power quality, as well as operational requirements regarding real and reactive power import and export. The microgrid as an entity and the microgrid control system shall satisfy these requirements.

For purposes of interconnection, a microgrid shall present itself to the grid to which it is connected as a single controllable entity. The control system is the system which achieves this goal. It satisfies the interconnection requirements using functions at the high level, core level, or low level of its function stack, see Figure 1. For example, the physical requirement to disconnect under certain voltage and frequency conditions will involve the core functions and the low-level functionality of individual devices, including breakers and disconnects.

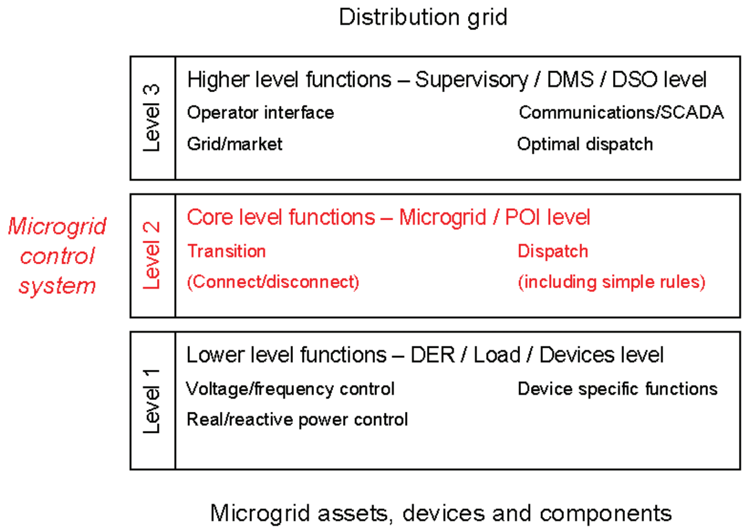

Figure 1—Microgrid control system functional framework

4.4 Defining microgrid control system core functions

The functions designated as core functions in this standard pave the way for a modular design of microgrid control systems through cohesive and platform-independent interfaces. This approach allows for flexibility and customization of control components and algorithms without limiting other potential functionality. Regardless of whether equipment and software are commercial or custom, it is necessary that components be interoperable and have interfaces that are congruent with the functional specification of the microgrid control system. The standard defines functions and their interrelationships that allow modularity and interoperability in physical implementations. It deals with the operation of the microgrid control system, and defines those aspects that need to be standardized; others can remain proprietary. The standard is functionality-driven and focuses on a modular approach that enables potential expansion and features.

Two core functions, which supervise the lower-level functions, are defined and specified in this standard:

a) The dispatch function, which dispatches individual devices in given operating modes and with specified setpoints.

b) The transition function, which supervises the transitions between connected and disconnected states, and ensures the dispatch is appropriate for the given state.

The core functions typically operate on a longer time scale than the lower-level functions. For example, a generator governor may adjust power output to maintain frequency while islanded, while the dispatch function may determine which generation assets must be operating in which modes and with which setpoints so that the governors can handle anticipated load changes.

In the case of permanently islanded microgrids, the transition function, related to connecting and disconnecting, is not used. The microgrid control system only implements the dispatch function, dispatching of microgrid assets and ensuring system stability.

The role of the microgrid control system is also to monitor the state of the system and notify the protection system of a change in state of the microgrid that may require a change in protection settings.

5. Functional requirements of a microgrid control system

5.1 General functional requirements

Any microgrid control system shall perform appropriate actions for the mode of operation of the microgrid, either steady state grid connected, steady state islanded, or during transitions between grid-connected and islanded modes. In this standard, the required behavior of the microgrid control system is discussed in terms of the functions it must perform. The core functions of the control system are the minimum functions necessary to meet the description of a microgrid as defined in this standard and based on the objectives listed above. The functions are abstract, and can reside anywhere within the physical microgrid control system. These functions are not necessarily limited to any particular physical control devices, and can be realized in centralized, decentralized, or hybrid architectures.

5.2 Core function interactions

The relationship and interaction between the dispatch and transition functions is provided in Figure 2. It indicates how the transition function calls upon the dispatch function during the transitions, as explained in the detailed description of the operation of the two core functions in the next subclauses.

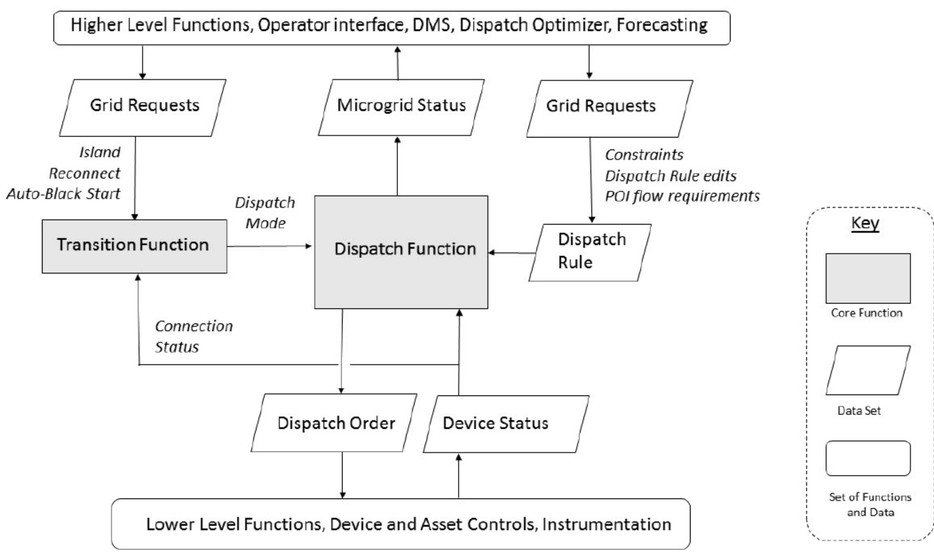

Figure 2—Relationship between transition and dispatch functions

5.3 General description of core functions

5.3.1 Dispatch of microgrid assets

The dispatch function includes the dispatching of microgrid assets and providing them with appropriate setpoints. It directs the use of the distributed energy resources available within the microgrid and ensures the proper operation of the microgrid, both internal to the microgrid and as seen by the grid at the POI with the distribution system. A dispatch order is basically a set of commands sent from the dispatch function to the microgrid assets or their individual controllers, see Figure 3. Examples of these commands include open or close, start or stop, set generation levels, and reduce load to critical loads only.

The control system shall dispatch microgrid assets according to operational requirements to serve installed or selected loads within the microgrid, in terms of power, while maintaining power quality requirements. In grid-connected mode it shall meet the interconnection agreement (in terms of energy consumed/produced) and interconnection requirements (power quality, e.g., harmonics and voltage sags) set by the distribution system operator and the microgrid internal requirements set by the microgrid owner/operator. The relevant requirements shall apply in the event of a planned or unplanned disconnection or islanding. In the case of an unplanned disconnection, the microgrid, as an entity, shall disconnect based on parameters specified in the interconnection requirements.

The dispatch core function provides the following functionalities: 1) balancing generation and load under normal islanded operating conditions; 2) re-dispatching controllable resources in response to internal events related to the load and generation profiles; 3) responding to external orders, for example interconnection agreement requirements, and external events by re-dispatching resources.

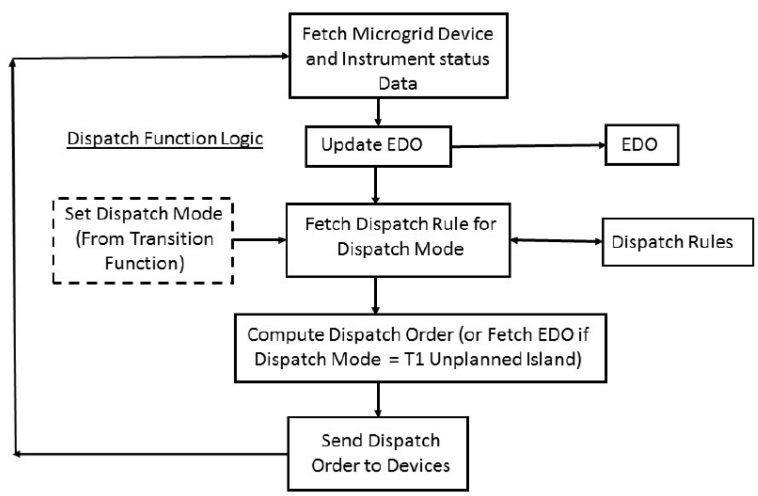

Figure 3—Dispatch function high-level logic

5.3.2 Transitions from grid connection to islanding

The transitions shall consider, as shown in Figure 4:

a) Unplanned islanding (T1)

b) Planned islanding (T2)

c) Reconnect (T3), with as applicable

d) Black start (T4)

The transition function provides the logic to switch the dispatch function between one of the relevant dispatch modes, which include the four transition modes (T1 to T4) and two steady state modes, the connected and islanded modes (SS1 and SS2), see Figure 4.

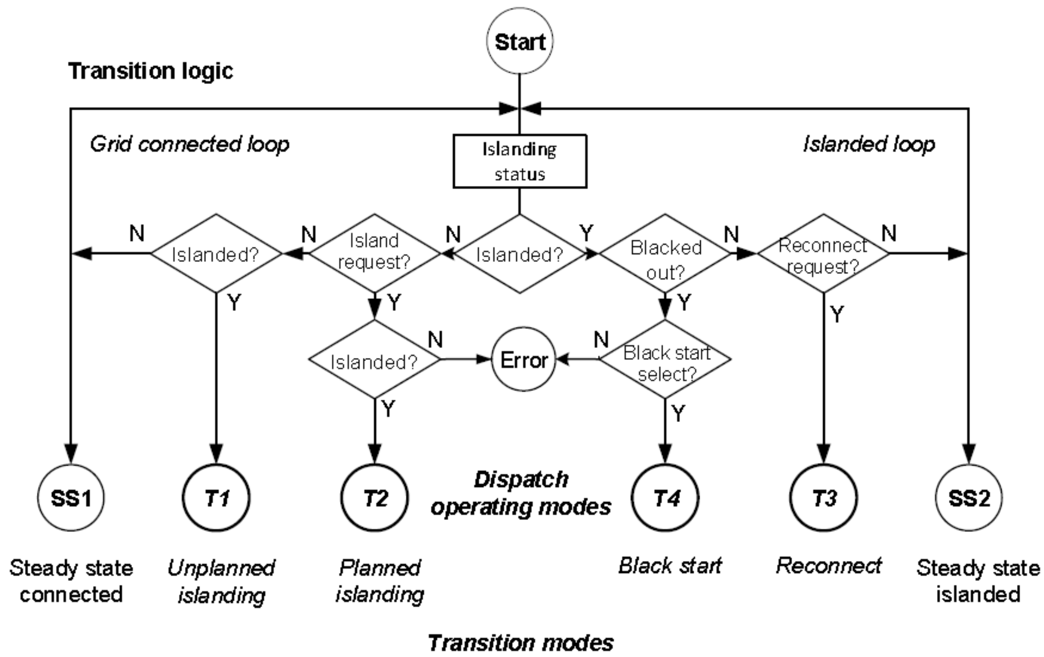

Figure 4—Sequences associated with the transition function

6. Dispatch function—dispatch of microgrid assets

6.1 Description and features of the dispatch function

The dispatch function shall include the required dispatching while connected, while islanded, and while transitioning between these two steady states. The dispatch function generates and executes dispatch orders which are sets of commands to appropriate microgrid assets in accordance with a dispatch rule, which may be considered a set of six rules, one for each dispatch mode set by the transition function (T1 to T4) and one for each steady state modes (SS1 and SS2), see Figure 4. To perform its functions, the dispatch function also receives microgrid system state information and, if necessary, estimates state information not directly observable.

The dispatch function, shown in Figure 3, receives as inputs the state of the microgrid and its components, the dispatch mode from the transition function, and a set of dispatch rules. Based on these inputs it calculates a dispatch order and sends it to the microgrid components as often as necessary.

The exception to the above process is in the immediate execution of an emergency dispatch order (EDO) upon being set to unplanned island dispatch mode by the transition function. This dispatch order may include changes in generation dispatch and load shedding as required to match available generation to emergency loads. This order is continuously updated as conditions change, and is available for execution without waiting to be computed. For example, as the percent of self-generation drops below a certain level, the EDO may be updated to immediately drop a certain low-priority load upon an unplanned island event. Since the EDO is pre-computed and continuously updated, the dispatch function executes the EDO immediately upon being switched to unplanned island dispatch mode. The EDO includes actions such as contingency load shedding.

The dispatch function operates on a longer time frame than the transition function of the microgrid, typically in the range of minutes, compared to the range of milliseconds for the transition function. They are implemented at the microgrid control system level as required.

6.2 Functional specification of the dispatch function

6.2.1 Overview

The characteristics of the dispatch function, including the elements and characterization of the function, are given in Table 1. Under steady state conditions, the dispatch function shall carry out the operations described below for the two states of the microgrid, grid-connected (SS1) and islanded (SS2), see Figure 4. During transitions, it receives information about the nature of the transition to be carried out and executes required operations. The transition modes include unplanned islanding (T1), planned islanding (T2), black start (T4), and reconnect (T3).

6.2.2 Grid-connected operation

The specific features in grid-connected operation shall include:

a) DER asset control/command, either individually or in a coordinated manner

b) Load management, curtailable loads

c) Dispatch control, either in the form of a look-up table or an optimization function (if applicable)

d) Operation of breaker, switches, and other switching and control devices, as applicable

e) Voltage regulation, using appropriate methods, including capacitor switching, transformer tap-changers, and the reactive power (var) produced by inverter-based interfaces

f) Implementation of power exchange levels (P, Q) at the POI

6.2.3 Island operation

The specific features in islanded operation shall include:

a) DER asset control/command, either individually or in a coordinated manner

b) Load management, curtailable loads

c) Dispatch control, either in the form of a look-up table or an optimization function (if applicable)—setting the net (P, Q) at the POI to 0

d) Operation of breaker, switches, and other switching and control devices, as applicable

e) Voltage regulation, using appropriate methods, including capacitor switching, transformer tap-changers, and the reactive power (var) produced by inverter-based interfaces

f) Frequency control using a reference microgrid generator or storage resource

g) Maintaining power quality levels, ensuring continuous monitoring of power quality levels, and taking appropriate remedial actions.

6.2.4 Transition modes

As indicated in 5.3.1, the dispatch function responds to external events by re-dispatching resources. Such events include transitions, see Figure 4. These modes of operation are associated with transitions described in 7.1. The relevant features of the dispatch function shall include:

a) Planned islanding (T2)—The dispatch function shall implement the relevant operations described in 7.2.2.

b) Unplanned islanding (T1)—The dispatch function shall implement the relevant operations described in 7.2.3. In particular, initiation of an unplanned islanding operation results in the immediate execution of an emergency dispatch order, as described in 5.1.

c) Reconnection to grid—The dispatch function shall implement the relevant operations described in 7.2.4.

d) Black start—This function is referenced in 7.1 and 7.2.5.

Table 1—Dispatch function requirements, characteristics, and metrics

Elements of the function	Function characterization	Parameters and metrics	Testing approach
Microgrid control system DER dispatch (generation, storage)	Implementing a DER dispatch table or algorithm	Microgrid control system response accuracy, settling time	Measuring control system performance in meeting objectives
Noncritical load management	Enforcing set points	P, Q, V, f (as applicable) at POI, steady state error	Measuring P, Q, V, f (as applicable) at POI, steady state values and error
Demand response	Enforcing load prioritization and curtailment	P, Q, V, f (as applicable) at POI, dynamic response (rise time, settling time, overshoot)	Measuring P, Q, V, f (as applicable) at POI, dynamic response (rise time, settling time, overshoot)
Microgrid control system dispatch performance	Dispatch function dynamic response	Compile responses, deviations in steady state, and transients	Comparing to metrics, quantifying deviations/errors
Power quality	Maintain power quality levels below set thresholds	Voltage and current harmonic distortion, individual harmonics, voltage sags, voltage swells, rapid voltage changes (RVC), flicker	Measuring voltage and current harmonic distortion, individual harmonics, voltage sags and swells, rapid voltage changes, flicker values/error
Data acquisition	Sensor response	Signal availability/accuracy	Signal measurement
Grid-connected operation			
DER assets control/ command	Individual dispatch	Meeting interconnection agreement, P, Q at POI	P, Q at POI
	Coordinated dispatch		
Load management	Load shedding, demand response	Meeting load demand	Meeting load demand control/regulation
	Load restoration		
Dispatch control	Look-up table	Meeting dispatch objectives	Verifying/quantifying objectives
	Optimization (as applicable)		
Breaker, switches—operation	Microgrid control system	Device status	Status signal availability
Voltage regulation	Capacitor switching, transformer tap-changing	Voltage regulation	Accuracy of voltage regulation, voltage tracking
Power exchange at the POI	Microgrid control system	Meeting P, Q requirements at POI	P, Q at POI
Islanded operation			
DER asset control/ command	Individual dispatch	V, f within range—load not served	V, f within range at POI (open), P, Q flows within
	Coordinated dispatch		
Load management	Load shedding, demand response	Meeting load demand	Emergency load shedding, amount

Table continues

Table 1—Dispatch function requirements, characteristics, and metrics *(continued)*

Elements of the function	Function characterization	Parameters and metrics	Testing approach
Dispatch control	Look-up table	Meeting dispatch objectives	Verifying/quantifying objectives
	Optimization (as applicable)		
Breaker, switches—operation	Microgrid control system commands	Device status	Signal availability, status
Voltage regulation	Capacitor switching, transformer tap-changing	Voltage regulation and deviations	Voltage regulation, voltage tracking and quality

6.3 Developing metrics for the dispatch function

The measurable quantities to which metrics are associated, for the dispatch function, Table 1, are:

a) Directly measurable quantities: voltage and current (time-domain waveforms)

b) Derived quantities: frequency, rms voltage, rms current, phase angle, real power (including direction of power flow), reactive power (leading or lagging), energy exchanged at the POI, power quality indices (voltage and current harmonic distortion, individual harmonics, voltage sags, voltage swells, rapid voltage changes [RVC], flicker), reference tracking errors

Requirements and metrics are discussed in B.3.

6.4 Scenarios for testing the dispatch function

Scenarios shall be defined for each of the following basic steady state dispatch operating modes shown in Figure 4 and described in Table 1:

a) Grid-connected operation—Variation of load and generation within the microgrid, impact on the operation and (P, Q) flows within the microgrid and the (P, Q) flows at the POI

b) Islanded operation—Variation of load and generation within the microgrid, impact on the operation and (P, Q) flows within the microgrid and the (V, f) fluctuations at the POI and within the microgrid;

For each of the basic dispatch modes, the dispatch function features, under function characterization in Table 1, shall be tested using measurable quantities, 6.3, allowing parameter values to be extracted and compared to metrics to determine conformance. Requirements and metrics are discussed in B.3.

The test scenarios shall consider the following conditions that should allow a complete and comprehensive testing of the dispatch function:

— The operation of the microgrid—These shall include the operating conditions before a specific test on the microgrid control system is performed: level of local generation and generation mix (dispatchable and non-dispatchable), operation of the storage device (mode of operation, state of charge), load composition (constant impedance, constant P-Q and active loads) and load mix (percentage composition), status of breakers, switches, and voltage control devices, and power (P, Q) exchanges between the microgrid and the grid (prior to a transition from grid-connected to island modes).

— The state of the grid at the time of the test is performed—These shall include the voltage at the POI and any disturbances occurring on the grid at the time of the transition.

The test scenarios shall consider the following inputs to the dispatch function:

- The constraints on dispatch function operation—These shall include: constraints in the steady state grid-connected mode of the dispatch function to implement successful unplanned islanding; constraints on the dispatch function imposed by appropriate physical assets.
- Dispatch rule edits required to change the priorities and logic of the dispatch rules for any of the dispatch modes—This is the manner in which a rule-based or optimizer-based dispatch function implementation is integrated into the test procedure.
- POI flow requirements (grid-connected mode)—A type of constraint reflecting the desired microgrid power exchange at the POI; this can be P and Q as a function of time, at a given voltage and frequency.

7. Transition function—from grid-connection to islanding

7.1 Description and features of the transition function

Since the microgrid control system shall meet the interconnection requirements and the microgrid internal requirements to serve installed or selected loads within the microgrid, the transition function shall not cause or delay a disconnection in a manner inconsistent with the interconnection requirements. The logic diagram illustrating the transitions, including the initiation and the final states, are shown in Figure 4.

As indicated in this diagram, transitions may be initiated by the following requests:

a) Planned islanding request (T2 mode)
b) Reconnect request (T3), with automatic black start (T4) enabled, as applicable

Transitions are also initiated by a system condition resulting in an unplanned islanding transition (T1).

After the transitions are completed, the microgrid operates either in a grid-connected mode (SS1, steady state connected mode) or in an island mode (SS2, steady state islanded). The relationship and trajectories between steady state and transition modes are further illustrated in Figure 5. The dispatch function operates during transitions.

As indicated in 6.2.4, the dispatch function shall operate during the transitions to implement the required dispatch of microgrid assets. One of the mechanisms is the emergency dispatch order used in the case of an unplanned transition (T1), as described in 6.1.

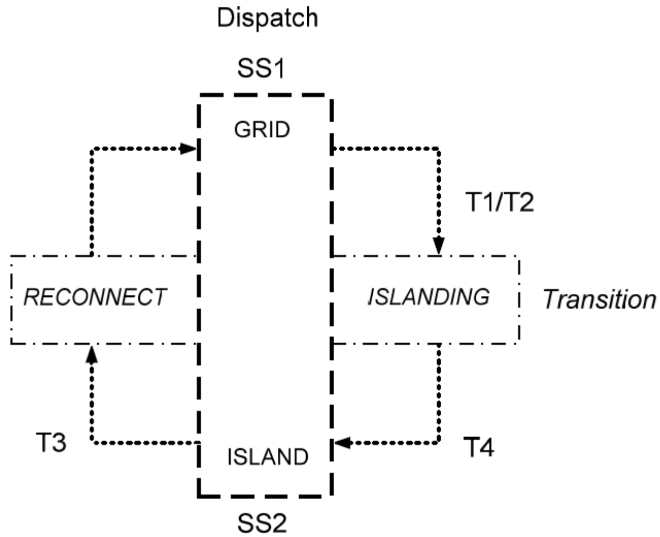

Figure 5—Interaction between dispatch and transition functions

7.2 Functional specification of the transition function

7.2.1 Introduction

The microgrid control system shall be able to carry out the operations described in Table 2 for the three transitions identified. These operations are characterized by the steps described below. The transition function logic required to switch the dispatch function between one of six dispatch modes is illustrated in Figure 4.

7.2.2 Planned islanding

The process and steps include:

a) Receive islanding command
b) Balance load and generation (adjust P and Q to both be 0 at the POI)
c) Set local controllers and protection devices appropriately
d) Create island
e) Transition to steady state islanded dispatch mode

7.2.3 Unplanned islanding

The process and steps include:

a) Detect islanded conditions
b) Create island
c) Set local controllers and protection devices appropriately
d) Execute required preplanned actions such as load shedding (and/or implement a black start if required)
e) Transition to steady state islanded dispatch mode

7.2.4 Reconnection to grid

The process and steps include:

a) Resynchronize, set/match voltage, phase angle, and frequency within prescribed limits specified by applicable grid codes or requirements

b) Set local controllers and protection devices appropriately

c) Reconnect

d) Transition to steady state connected dispatch mode and restore non-critical loads as appropriate

7.2.5 Black start

Black start is implemented if required. Black start steps are unique to each microgrid and are not specified in this standard.

Table 2—Transition function—requirements, characteristics, and metrics

Elements of the function	Function characterization	Parameters and metrics	Testing approach
Transition initiation	Planned or unplanned	Microgrid control system response accuracy and settling time	Measuring control system response
Balancing load and generation, as required	Change in DER/load dispatch orders (as required)	P, Q, V, f (as applicable) at POI, steady state error	Measuring P, Q, V, f (as applicable) at POI, steady state error
Transition to new operating condition	Change in DER/load dispatch orders (as required)	P, Q, V, f (as applicable) at POI, dynamic response (rise time, settling time, overshoot)	Measuring P, Q, V, f (as applicable) at POI, dynamic response (rise time, settling time, overshoot)
Controller returning, new device settings (as required)	Look-up table or equivalent	Compile responses, deviations in steady state and transients	Verify as required
Data acquisition	Sensor response	Parameter availability	Parameter accuracy
Planned islanding			
Step 1—initiation	Receive islanding command	Control signal reception	Verify receipt of command, time received, intervention time
Step 2—internal balancing	Balance load and generation (adjust P, Q to be 0 at POI)	Balance load/generation (P, Q) in microgrid, reaction time	Verify signals as required
Step 3—returning	Set local controllers and protection devices appropriately	Signals sent, changes implemented	Verify signals as required
Step 4—moving to island mode	Island creation	POI connection opens	Verifying POI opening, reaction time
Step 5—returning to normal operation	Transition to steady state islanded dispatch mode	V, f within range; power quality values below thresholds—dispatch orders	Observe V, f, transient response (rise time, settling time, overshoot) and power quality levels
Unplanned islanding			
Step 1—initiation	Detect islanding conditions	Control signal receipt	Verify receipt of command, time received, intervention time
Step 2—returning	Set local controllers and protection devices appropriately	Signals sent, changes implemented	Verify signals as required

Table continues

Table 2—Transition function—requirements, characteristics, and metrics *(continued)*

Elements of the function	Function characterization	Parameters and metrics	Testing approach
Step 3—moving to island mode	Execute preplanned actions such as load shedding (implement a black start if required)	POI connection opening	Verifying POI opening, reaction time
Step 4—returning to normal operation	Transition to stead state islanded dispatch mode	V, f within range; power quality values below thresholds—dispatch orders	Observe V, f, transient response (rise time, settling time, overshoot) and power quality levels
Reconnection			
Step 1—initiation	Resynchronize, match voltage, phase angle, and frequency within prescribed limits	Difference (V, phase angle), rate of change of angle or frequency difference, within limits	V, phase angle, rate of change of phase angle or frequency difference, response time
Step 2—returning	Set local controllers and protection devices appropriately	Signals sent, changes implemented	Verify signals as required
Step 3—moving to grid-connected mode	Reconnect	POI connection closing	POI closed, verify initial P, Q flow, reaction time
Step 4—moving to normal operation	Transition to steady state connected dispatch mode and restore non-critical loads	V, f within range; power quality values below thresholds—dispatch orders for grid connected mode	Verify final P, Q flow, settling time; observe power quality levels

7.3 Developing metrics for the transition function

The measurable quantities and associated metrics for the transition function, Table 2, are:

a) Directly measurable quantities: voltage and current (time-domain waveforms)

b) Derived quantities: frequency, rms voltage, rms current, phase angle, real power (including direction of power flow), reactive power (leading or lagging), energy exchanged at the POI (grid-connected mode), power quality indices (voltage and current harmonic distortion, individual harmonics, voltage sags, voltage swells, rapid voltage changes [RVC], flicker), reference tracking errors

Requirements and metrics are discussed in B.3.

7.4 Scenarios for testing the transition function

Scenarios shall be defined for each of the following basic transitions:

a) Grid connected to islanded–planned islanding—This transition is initiated upon receipt of an external request, typically sent by the distribution system or microgrid operator.

b) Grid connected to islanded–unplanned islanding—This transition is the result of an event on the distribution grid. It can involve a black start if the control system is designed in this manner.

c) Islanded to grid connection—This transition involves resynchronization and reconnection of the microgrid.

For each of the basic transitions, the transition function features, under function characterization in Table 2, shall be tested using measurable quantities, 6.3, allowing parameter values to be extracted and compared to metrics to determine conformance. Requirements and metrics are discussed in B.3.

As indicated in the functional specification of the dispatch function, 6.2.4, the relevant features of this function are also executed during transitions. Therefore, the scenarios developed to test the transition function shall also necessarily test the associated features of the dispatch function.

The test scenarios shall consider the conditions indicated below. They are chosen to allow a complete and comprehensive testing of the transition function, including the required and relevant features of the dispatch function:

- The initial operating conditions of the microgrid—These include the operating conditions before the transition occurs: level of local generation and generation mix (dispatchable and non-dispatchable), operation of the storage device (mode of operation, state of charge), load composition (constant impedance, constant P-Q, and active loads) and load mix (percentage composition), status of breakers, switches and voltage control devices, power (P, Q) exchanges between the microgrid and the grid (prior to a transition from grid connected to island mode).
- The state of the grid at the time of the transition—These include the voltage at the POI and any disturbances occurring on the grid at the time of the transition. In the case of an unplanned islanding event, the nature of the event (typically a fault or an open connection on the feeder connected to the POI) initiating the islanding transition is considered.

Annex A

(informative)

Microgrid description

A.1 Microgrid structure

A microgrid is a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes (see Figure A.1).

The electrical circuit shows one connection to the distribution grid at the point of interconnection (POI). This is the point at which the microgrid interacts with the distribution as defined in this standard. It is acknowledged that multiple connections including an alternate utility connection at the substation can exist. However only one of the connections with the distribution grid will be closed at a given time.

A comprehensive discussion of microgrid connections to a distribution grid is given in Figure 1, Examples of DR island systems, of IEEE Std 1547.4™-2011. It complements Figure A.1 and presents a hierarchical structure. The different possible configurations are listed in A.3.

Figure A.1 shows the typical components of the microgrid, including different types of DER and loads. These are described below. The interface between the microgrid and the distribution system is depicted as a breaker. The figure also includes the microgrid control system and shows its connection to the different components of the microgrid, including breakers.

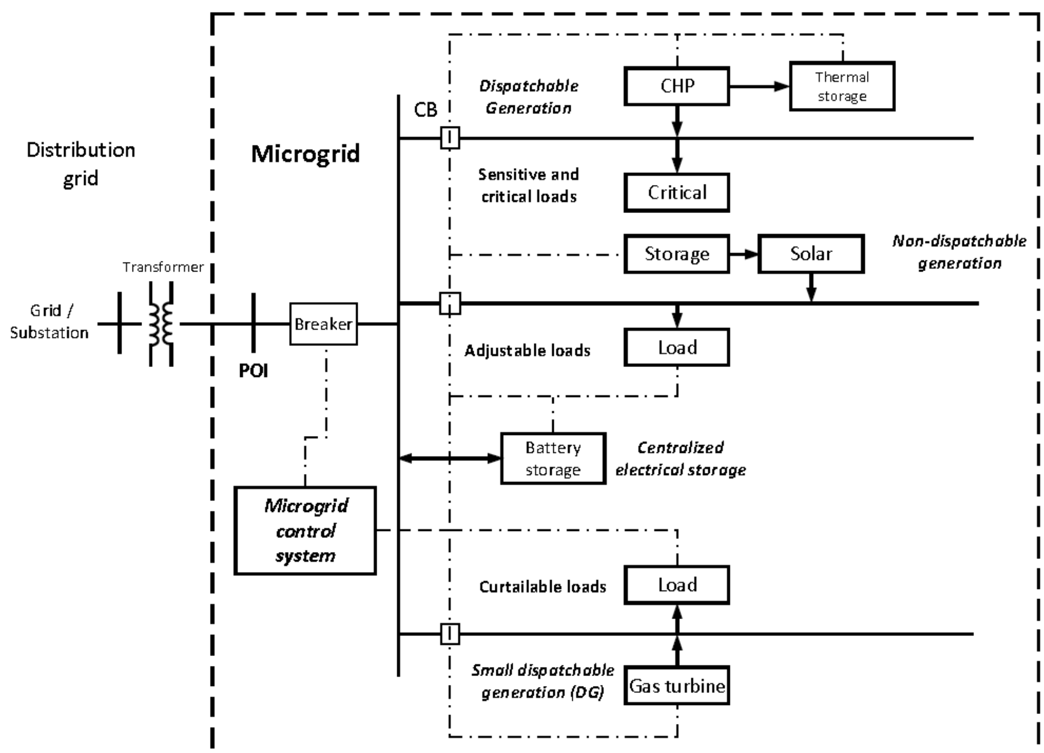

Figure A.1—Microgrid structure and components

A.2 Microgrid components

A.2.1 Loads

Microgrid loads are categorized into different types, in terms of their criticality and controllability:

a) Critical loads—These are loads that must be served in all normal operating modes of the microgrid. They typically cannot be curtailed. Examples are information technology (IT) and computer power, building controls, security systems, and life-safety systems (e.g., egress lighting).

b) Priority loads—These are loads that may be curtailed if necessary, but should be satisfied if possible.

c) Controllable loads—These are loads that can be periodically interrupted or set at various load levels. Examples are heating, ventilation, and air conditioning (HVAC) system loads (chillers, air handlers) and non-essential industrial process equipment. The operating points of building HVAC systems can be adjusted to provide controllable loading. For example, a building with excess photovoltaics (PV) generation capacity in the morning can cool a building to a lower temperature and then use this stored thermal energy to offset afternoon heat load.

d) Interruptible loads—These are loads that can be shed or interrupted at any time to allow generation to satisfy high demand. Examples include thermal energy storage, water pumping where sufficient tank storage is available, and charging of batteries in distributed energy storage (DES) devices.

e) Diversion and dump loads—These loads are used when excess generating capacity is available, and curtailment of generation is either not possible, or where there is economic benefit to use the diverted energy. An example is a diversion load for a wind turbine that absorbs gust energy.

f) Undefined loads—Other loads not defined above, including loads with undefined characteristics.

A.2.2 Distributed energy resources (DER)

Distributed energy resources, comprising generation and storage, include the following:

a) Distributed generation (DG)—Categorized into two types: a) dispatchable units, which can be controlled by the microgrid control system and are subject to technical constraints, depending on the unit type, such as capacity limits, ramping limits, minimum on/off time limits, and fuel and emission limits, and b) non-dispatchable units, which cannot be controlled by the microgrid control system since the input source is uncontrollable. Non-dispatchable units are mainly renewable resources which produce a variable and intermittent output power. These characteristics negatively impact the non-dispatchable unit generation capacity and increase the forecast error, therefore these units are commonly reinforced with DES systems. Examples include:

    1) Mechanically-driven synchronous and induction rotating electrical machines—These include machines with diesel, spark-ignition and turbine prime movers, direct-connected wind turbines, and common-shaft dc-ac power conversion equipment. The most common example is a diesel-generator set with a synchronous ac electrical generator. Another example is the doubly-fed induction machine used for wind generation.

    2) Combined heat and power (CHP), also called *cogeneration*, where both thermal and electric energy from the generator is used. Control of a CHP plant may differ from a simple electrical generator as thermal demand can drive loading and scheduling.

    3) Inverter-based systems that convert dc to ac power—Examples include inverters fed by PV, fuel cells, and wind turbines with variable-speed electronic drive trains. Some variable speed wind turbines have ac-dc (rectifier) and dc-ac inverter stages.

b) Distributed energy storage (DES)—The primary application of the DES is to coordinate with DGs to enable microgrid generation adequacy. It can also be used for load shifting, where the stored energy at times of low prices is generated back to the microgrid when the market price is high. The DES also plays a major role in microgrid islanding applications.

c) Undefined DER—Other types of DER producing electrical power not defined above, including DER based on multi-energy systems.

A.2.3 Control elements

The control elements include the following:

a) Microgrid control system—The microgrid local controller is a decision-making software and/or hardware of the microgrid. The scheduling of microgrid DER in grid-connected and islanded modes is performed by the controller based on economic and reliability considerations. Microgrid controller determines the microgrid interaction with the utility grid, the decision to switch between grid-connected and islanded modes, frequency regulation and voltage control, and optimal operation of local resources. It also provides any decisions on load curtailment/shifting.

b) Additional sensor, communication, and control elements—These include smart switches, communications networks, etc.

A.3 Types of microgrids

A.3.1 Introduction

Micrograms can be implemented in many different environments and can take many forms. An example of geographically constrained electric grid which has minimal impact on and interaction with the electric grid is a large industrial plant. Such plants have been operating for many years with an energy management system that manages the internal operations.

A comprehensive discussion of possible hierarchical islandable structures is found in IEEE Std 1547.4™-2011 where Figure 1, Examples of DR island systems, shows several operating configurations for island systems that incorporate DER. The island systems in the figure include local electric power system (EPS) island (facility island), secondary island, lateral island, circuit island, substation bus island, substation island, and adjacent circuit islands. These systems are covered in the referenced guide.

Microgrids can be categorized into different groups based on the type of customers (such as campus, military, residential, commercial, and industrial), application (such as premium power, resilience-oriented, loss reduction, etc.), connectivity (remote and grid-connected), and the type of voltages and currents adopted in the microgrid (such as ac, dc, and hybrid). All of these microgrids utilize a control system that includes the core functions defined in this standard.

Microgrids may be either utility or non-utility owned. Non-utility owned can be private, community, public, or any viable business type as defined by and in the jurisdiction in which the microgrid is installed.

A.3.2 Large self-contained complexes

These systems exchange power with the grid (buying and selling under contract, for example), have enough local generation to operate in islanded mode, usually only serving part of the load, and can provide ancillary services to the distribution grid. They can include large commercial and industrial installations (processing plants, ports), large building complexes, larger mixed use (commercial and residential) urban areas, utility distribution microgrids, institutional and government installations (research centers, hospitals, and prisons), university campuses, and critical infrastructures (military, hospital).

A.3.3 Community microgrids

They include renewable distributed generation, distributed or centralized storage, and controllable loads.

A.3.4 Remote and isolated communities and installations

They typically include conventional generation (diesel generators) and renewable generation. They are not grid connected and do not exchange power with surrounding electric transmission or distribution grids. They can be considered as net-zero distribution grids, but need a microgrid control system if they have multiple sources of power, including diesel (usually the base-load generator) and non-dispatchable renewable energy resources (wind, solar). They can integrate energy storage as a means of balancing loads and intermittent and variable generation. Since the microgrid is not connected to a distribution grid, the control system does not include the functions required to interact with the grid.

A.4 Microgrid reference models and benchmarks

For the purposes of this standard and for establishing a functional specification and a set of testable functions, the reference microgrid shall contain the minimum basic elements that define a microgrid, as per definition, and microgrid basic structural diagrams.

Annex B

(informative)

Objectives of the microgrid and control system

B.1 Introduction

A comprehensive microgrid functional specification can be developed by identifying the core objectives of the microgrid control system, and the electric grid elements with which the microgrid control system will interact.

The objectives of deploying a microgrid are implicit in the business case, based on and quantified in terms of economics and other identifiable benefits to stakeholders. In some cases, other less easily quantifiable benefits may be used, including reliability, energy security, and resilience to extreme atmospheric events. The objectives will also depend upon the microgrid features, including sustainability, and net consumer or net generator of outside power.

Objectives define the functional specification.

One approach to systematically develop the business case and define the microgrid and microgrid controller objectives is the use case approach. This is a systematic procedure that identifies the following:

a) Stakeholders—These include: the microgrid customers and end users, the distribution grid customers and loads, the independent power producers (IPP) within the microgrid, and the distribution system operator (DSO). Society may also be a beneficiary.
b) Benefits—These are typically associated with supplying secure and reliable energy, and maintaining power quality within the microgrid. They also include power exchanges established with the distribution system and ancillary services provided to the distribution system.

Benefits in turn define the objectives and functions of the microgrid and the microgrid control system.

The benefits of a microgrid have been broadly classified as improved energy efficiency, reduced emissions, and improved power quality and reliability, and increased energy security and resilience. Energy cost reductions may also be achieved. Reduced emissions result from the different generation mix of distributed energy resources (DER), including battery energy storage system (BESS) and the distributed generators (DG), based on renewable energy resources (namely solar and wind). Reduced emissions are achieved by maximizing power produced from lower-emitting sources. From identified impacts, economic benefits can be obtained through participation of microgrid loads and power sources (generators) as one co-operating entity. This also allows optimization of energy costs based on participation in the electricity market, reducing or offsetting substation and feeder loading, and provision of ancillary services to the grid. Some examples of ancillary service provisions include reactive power production and voltage control, provision for back-up and reserve power, black start capability, as well as potentially working on a larger scale to provide frequency control reserves.

B.2 Approach to specifying objectives of the microgrid and control system

The use case paradigm can be applied to the evaluation of the benefits, objectives, and operational features of a microgrid to explicitly define and quantify the benefits and value of a microgrid investment for identified stakeholders, and establish the business case. Every microgrid is unique and has its own specific set of benefits and impacts. These impacts are associated and allocated to specific stakeholders through the benefits that accrue to them. This process provides a quantified valuation of the benefits of the microgrid from the perspective of each stakeholder.

The objectives of the microgrid can be realized by means of a microgrid control system. It provides control, regulation, and dispatch (and optimization, as applicable) functions for the microgrid components during the four modes of operation: grid connected, transition to island, island, and transition to grid connected. While grid connected, the microgrid controller will provide services both to the loads and DER inside the microgrid (behind the POI) and to the distribution grid.

The area regulation services offered by the microgrid will provide security and stability to the distribution grid by balancing external load or renewable generation variations within the grid. These ancillary services could include frequency and voltage regulation, either autonomously or under direct control of the distribution system operator, demand response, spinning reserve, load control, and black start capability for the local distribution grid.

The microgrid control system will also increase stability within the microgrid by providing enhanced real-time feedback control of the DER. It will send real and reactive power commands to smart inverters to compensate for power variations inside the microgrid.

The microgrid control system could participate in a local distribution retail power market by bidding its electric energy and power and ancillary services into the electricity market.

Voltage profile control, frequency control (in island mode), phase imbalance control, and active control of harmonic distortion may be desirable features within the microgrid system area. These functions will differ between grid-connected and islanded operation. The active control of harmonic distortion will typically reside within the end DER devices; the microgrid controller may play a supervisory role.

B.3 Deriving requirements of control system functions

B.3.1 Introduction

The more important stakeholders are the microgrid owner and operator, microgrid customers and operators of the DER within the microgrid, and the distribution system operator (DSO), typically the local utility, the owner and operator of the assets to which the microgrid is connected, and with which the microgrid interacts. In the case of isolated microgrids, the only stakeholders are within the boundaries of the microgrid.

B.3.2 DSO interconnection requirements and agreements

A microgrid that is not utility owned only connects to a distribution grid if it meets the relevant grid codes and/or an interconnection agreement that has been worked out with the DSO. This agreement establishes the following:

a) The conditions under which a connection is allowed and the requirements imposed on the microgrid control system—The microgrid operation should not negatively affect the power quality of the distribution grid, jeopardize its energy security, or reduce its reliability. The microgrid can also be required to provide grid support at the point of interconnection (POI).

b) Financial arrangements regarding energy imports from the distribution grid and exports (sales) to the grid—They also define the conditions under which ancillary services are provided and the financial compensation paid to the microgrid operator for these services.

c) Information required by the distribution management system (DMS)—This is required to allow monitoring and possibly control of the microgrid in its interaction with the distribution grid and DMS during steady state operation and the connection (reconnection) and disconnection (islanding) processes. This information may also be required by the DER management system (DERMS) if applicable.

B.3.3 Microgrid owner/operator requirements

The microgrid control system requirements include the following:

a) Energy management and optimization within the microgrid—Priority-based dispatch, with or without optimization as applicable, based on cost, reliability, resiliency, among others for on-grid and off-grid operation

b) Planned and unplanned transition to/from grid connected or island modes

c) Supplying premium quality power for both modes and stable operation in island mode

End users within the microgrid benefit from reductions in energy cost (including cost reductions associated with the use of demand response), and improvements in reliability and power quality.

Independent power producers (IPP), or owners of DER, and microgrid operators benefit from energy sales profits, and may benefit from the proceeds of contractual agreements for the provision of reliability, power quality, or other services or participation in other markets (for example, emissions markets).

B.3.4 Distribution system requirements for the microgrid

The conditions under which a connection is allowed and the requirements imposed on the microgrid control system are typically dictated by the distribution system operators. One of the most important requirements is that the microgrid operation does not negatively affect safety, the power quality of the distribution grid, jeopardize its energy security, or reduce its reliability. The microgrid can also be required to provide grid support at the POI.

Distribution grid customers and the DSO benefit from improved reliability; for example, when the microgrid provides real power to an adjacent section of the external grid that has experienced loss of power from the upstream network. Customers may benefit from improved power quality; for example, when the microgrid injects reactive power as part of a voltage-support service. Benefits may also accrue from deferred investment and upgrade costs.

B.3.5 Other standards and requirements

In the absence of applicable utility grid codes and requirements, IEEE Std 1547 provides interconnection and interoperability technical and test specifications and requirements for distributed energy resources (DER) and discusses the disconnection and reconnection of DER. It recognizes the newly established smart inverter functionalities. Other relevant standards include UL 1741 (SA) Ed 2. Power quality and flicker issues are addressed in standards such as IEEE Std 1453™.

B.4 Specific objectives of the microgrid control system

B.4.1 Introduction

The objectives of the microgrid control system are directly related to the business case and the capability of the microgrid to provide various types of services. The objectives may not be directly quantifiable or controlled, in which case they are not directly related to a microgrid control system function. In other cases, microgrid objectives are related or interconnected. In such a case, a given control system function can be designed to implement several objectives simultaneously.

B.4.2 Services to the microgrid customer

B.4.2.1 Resilience, energy security, and reliability

Because these features are the result of specific system and component design approaches and choices at the planning and implementation stages, increased resilience, energy security, and reliability cannot necessarily be obtained by means of specific control system functions. However, the consequences of operating a microgrid can be increased resiliency and reliability of the power supply within the microgrid, detailed as follows:

a) Resilience
   1) Minimum requirements: Backup power during extreme, infrequent, and long-duration outage events—Basic considerations: i) Metrics: system uptime; ii) Providing backup power for critical loads (if such loads exist); iii) Black start of the microgrid in islanded mode (if the equipment capability exists within the microgrid)
   2) Additional services: i) Backup power for priority/critical loads; ii) Load shedding; iii) Optimizing islanding duration; iv) Minimizing load not served; v) Providing time for controlled shutdown of loads following a distribution system outage
b) Reliability
   1) Minimum requirements: i) Uninterrupted power/seamless islanding (a minimum requirement for some customers)
   2) Additional services: i) Backup power during regular, frequent outages; ii) Improvement of System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Consumer Average Interruption Frequency Index (CAIFI) numbers; ii) Uninterrupted power and/or seamless islanding
c) "Downstream" power quality—additional services: i) Mitigation of voltage/frequency sags and surges; ii) Mitigation of harmonics (voltage and/or current, if required)

B.4.2.2 Reduction of overall energy costs—optimization function

The optimization function includes the following:

a) Reduction of energy costs by optimizing resource usage: i) Optimizing utilization of DER; ii) Day-ahead bidding and scheduling; iii) Unit commitment; iv) Managing electricity and heat, combined
b) Reduction of losses: i) Voltage profile optimization within the microgrid; ii) conservation voltage reduction (CVR), if applicable; iii) Feeder loss minimization; iv) Load shifting/time-of-use optimization
c) Reduction of demand charges: i) Energy price arbitrage; ii) Peak shaving
d) Capturing credits/payments on services: i) Ancillary service payments; ii) Market credits; iii) Renewable energy credits; iv) Maximizing renewable energy resource utilization (PV, wind); v) Carbon credits; vi) Minimizing greenhouse gas emissions

B.4.3 Services to the microgrid operator

B.4.3.1 Grid-connected mode—minimum interconnection requirements

The minimum interconnection required functions built into the microgrid control system are the following:

a) Compliance with DSO interconnection rules: i) Power import/export limits; ii) Generation ramp rate limits; iii) Low/high voltage ride-through requirements (potentially only a requirement for microgrids that export power); iv) Low/high frequency ride-through requirements (potentially only a requirement for microgrids that export power)

b) Voltage regulation and support at the POI (if required)

B.4.3.2 Grid-connected mode—additional services

The additional services provided in grid-connected mode include the following:

a) Optimal power flow (OPF): i) Location-based distributed generation dispatch; ii) Line loss minimization

b) Response to real-time signals (and requirements) from the transmission (TSO signals to DSO) or the distribution levels

B.4.3.3 Islanded operation—minimum requirements

The minimum requirements in islanded mode include the following:

a) Protection coordination (if relevant): Protective relaying for fault protection is a device-level control function; the microgrid control system only provides supervisory/coordination control

b) Voltage regulation: Performing volt/VAR control, volt/watts control, making use of available resources

c) Stability in meeting demand (if relevant): i) Emergency load shedding; ii) Frequency regulation when islanded; iii) Voltage regulation when islanded; iv) Voltage profile control—Coordinated load tap changers, DER, and capacitor banks

d) Priority-based energy management

e) Balancing of generation and load: i) Unit commitment; ii) Optimal power flow—operation under system distribution constraints; iii) Spinning reserve/regulation management; iv) Short-term look-ahead (15 min to 1 h), required for microgrids with variable renewables; v) Load control, may be required, depending on how much generation and reserves are available on the microgrid; vi) Load shedding; vii) Demand response

B.4.3.4 Islanded operation—additional services

The additional services provided in islanded mode include the following:

a) Priority-based energy management

b) Dispatch and forecasting, load balancing: i) Economic dispatch; ii) 5- or 10-min schedules for 1 h; iii) Short-term look-ahead (15 min to 1 h); iv) Long-term (1 d to 1 week); v) Micro-locational weather forecasting; vi) Balancing of generation and load; vii) Intelligent load shedding; viii) Demand response; ix) Line loss minimization

B.4.3.5 Transition from grid connected to islanding—minimum requirements

The minimum requirements for a transition from grid connected to islanding modes include the following:

a) Seamless transition (requirement for some loads): i) Fast load shedding—alternative is hardening of the loads (e.g., via uninterruptible power supply); ii) Closed transition (requirement for some customers); iii) Synchronization for grid reconnection

b) Open transition: Shut down DER, close the point of common coupling (PCC) to re-energize the loads, then restart DER

c) Protection coordination, as applicable

d) Intentional islanding—requirement for some high-value customers: Ensuring stability upon segmentation

B.4.3.6 Transition from grid connected to islanded mode—additional services

The additional services that can be provided in the transition from grid connected to islanded modes include the following:

a) Fast load shed upon loss of utility—may not be a requirement

b) Optimization criterion for operating point: i) Minimize greenhouse gas emissions; ii) Maximize reliability; iii) Maximize resilience; iv) Minimize maintenance/service trips; v) Minimize fuel cost; vi) Minimize audible noise; vii) Maximize equipment life (e.g., battery storage cycle life, generator run hours)

B.4.4 Services to the distribution system operator

The services provided to the distribution system operator include the following:

a) Minimum requirements: i) Maintain power import/export limits (balancing); ii) Prevent unsafe back feed of the distribution system; iii) Protection coordination—relaying for isolating faults within the microgrid

b) Additional services: i) Aggregated ramp rate control at the POI; ii) Peak demand reduction/maintaining constant load; iii) “Upstream” power quality; iv) Demand response: day-ahead; real-time (automatic demand response); interruptible load, utility event response; v) Voltage regulation at the POI; vi) Phase balancing

Annex C

(informative)

Implementation of the control system functions

C.1 General classification and assignment of functions

To meet the objectives of the microgrid operation, the control system needs to perform specified tasks or functions. These operate at different levels in the microgrid operating strategy (Figure C.1). The implementation of these functions is carried out in different hardware and software platforms, depending upon the design of the microgrid. The abbreviations used in the function assignment are:

— EPS: electric power system

— AGC: automatic generator control

The grouping of these functions varies with implementation choices, see Figure C.1.

Smart inverter functions associated with some of the functions listed in the function assignment blocks are described in standards such as IEEE Std 1547 and UL 1741 (SA) Ed. 2.

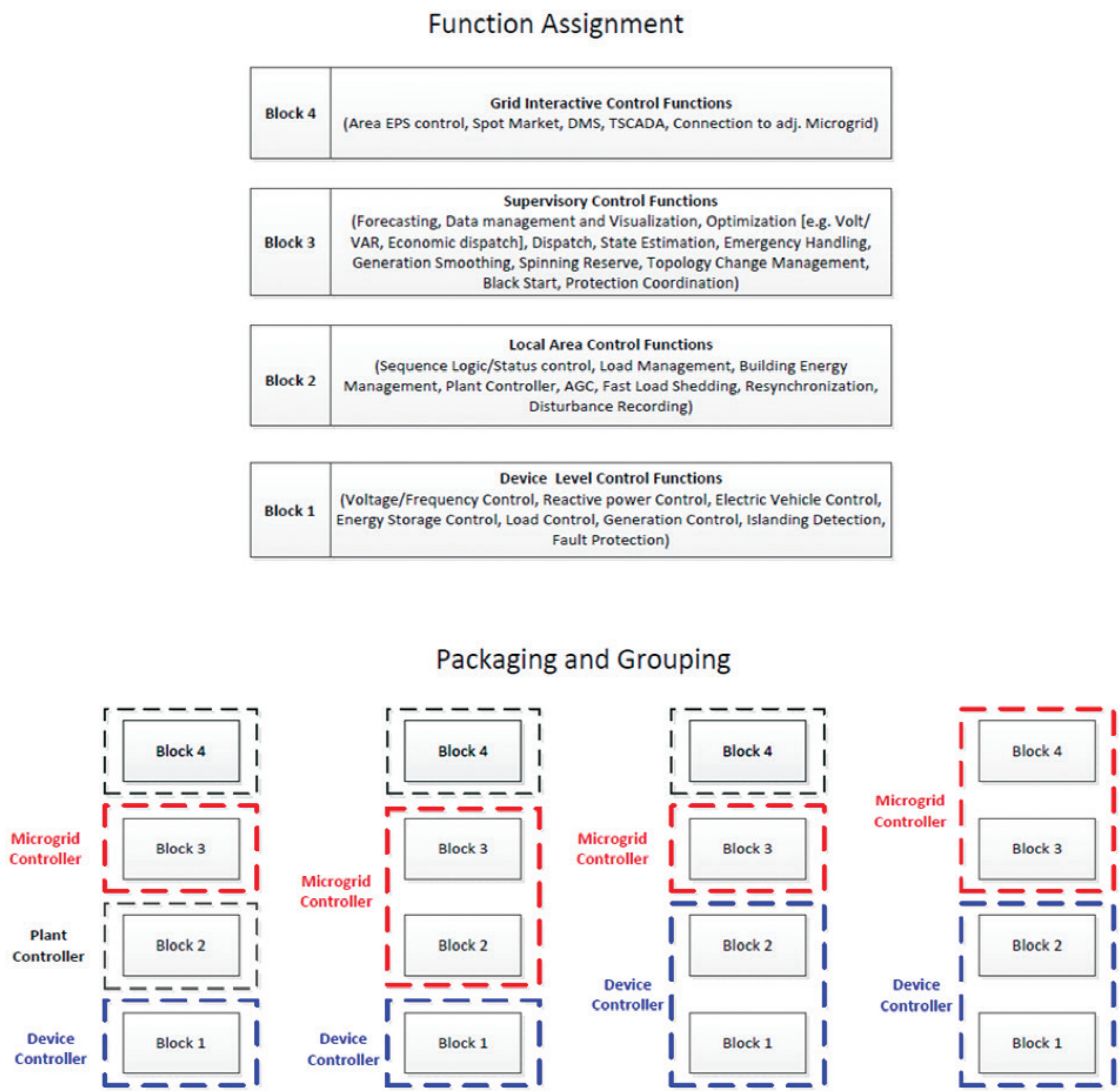

Figure C.1—a) function assignment, b) function grouping options

C.2 Function grouping and packaging

Generally, the management of a functional microgrid can be done through several layers, such as, device layer (sources, loads, switches, etc.), local controller layer (load aggregators, microgrid energy management system, etc.), supervisory controller layer (microgrid control system, etc.) and high-level grid interface layer (markets participation in transmission level, etc.). In this standard, these functions are categorized into four function blocks, shown in Figure C.1 (a) as follows:

a) Block 1—Device-level control functions

b) Block 2—Local-area control functions

c) Block 3—Microgrid supervisory control functions

d) Block 4—Grid interactive control functions

It should be noted that the functions in lower-level blocks are more likely to be applied directly on the hardware (devices and assets), and the functions in higher-level blocks are more likely software based and applied through the lower-level functions to the hardware.

The device-level control functions in Block 1 acts in the range of micro-seconds to seconds and results stable and safe operation of the connected equipment. These functions are usually directly realized through a device-level controller, such as distributed energy resources (DER) controller, inverter controller, load and line switch controller, energy storage controller, microgrid switch controller and relays, but with dispatching orders from the higher-level controllers.

The hierarchical and prioritization of device and/or aggregated functions in the microgrid control system is an implementation issue that is left to the control system designer and is not covered in this standard. It depends upon the level of intelligence built into the devices and the control system design. Among the options are the centralized and decentralized approach. In the centralized approach, most of the intelligence can be concentrated into the controller, whereas in the decentralized approach, much of it may reside in the devices. The functions listed in the four blocks are conceptual functions that can reside in different hardware and software components that make up the microgrid control system.

The operating conditions and modes of the microgrid control system will define the specific functions executed at any one time. Operating modes covered in this standard are grid-connected and islanded modes. Other modes can be considered, such as the transfer of the microgrid from one feeder to another. Such modes will require identification of the mode and adjustment of the control system parameters if required.

The functions represented in Figure 1 in relation to the functional framework of the microgrid control system are groupings of the conceptual functions listed in Figure C.1 that are required to implement the two core-level functions defined in this standard. Figure 1 also groups the functions with which the core-level functions interact into Level 1, lower-level functions, and Level 2, higher-level functions. The operation of core-level functions may rely on functions described in Blocks 1, 2, and 3 of Figure C.1. Higher-level functions are mostly associated with Bock 4.

C.3 Control function implementation time frame and time scale

These four blocks of functions have different action domains. Compared with the primary, secondary, and tertiary control in transmission systems, the device-level control functions act in micro-seconds to seconds' range and can be seen as the primary control of a microgrid. The local-area control functions and microgrid supervisory control functions act in seconds to days/a week's range and can be taken as the secondary control. Finally, the grid interactive control functions act in the minutes to days or a week's range and can be seen as the tertiary control. The action domains of these functions are shown in Figure C.2.

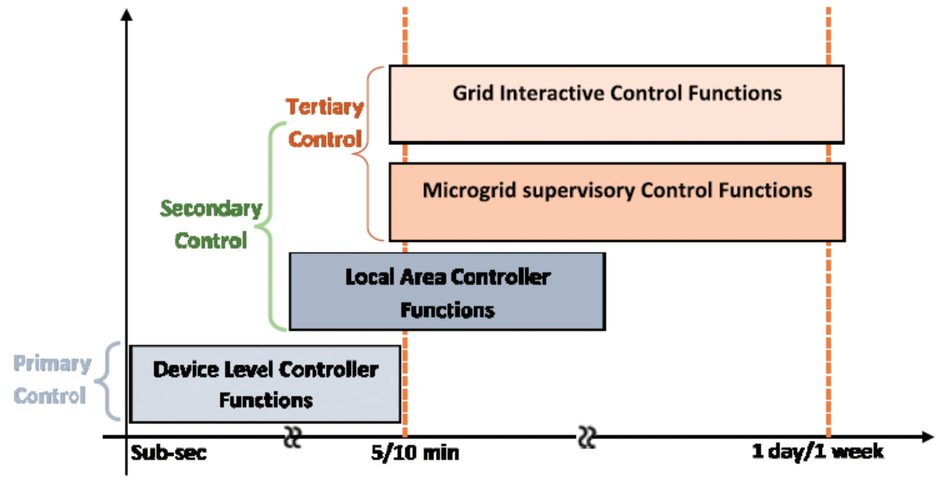

Figure C.2—Microgrid control system time frame and action time domain

Annex D

(informative)

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