A Generic Microgrid Controller

Generic Microgrid Controller Specifications

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List of Acronyms and Abbreviations

ACE	Area Control Error
AGC	Area Generation Control
APEP	Advanced Power and Energy Program
AVR	Automatic Voltage Regulators
BC	Breaker Controller
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DOE	U.S. Department of Energy
EDO	Emergency Dispatch Order
GC	Generation Controller
GMC	Generic Microgrid Controller
LC	Load Controller
MMC	Master Microgrid Controller
NETL	National Energy Technology Laboratory
PCC	Point of Common Coupling
POI	Point of Interconnection
SC	Storage Controller
UCI	University of California, Irvine
VFD	Variable Frequency Drive

1 Introduction

This functional specification for a Generic Microgrid Controller (GMC) is produced under U.S. DOE Grant DE-OE0000730 which was awarded to a team led by the Advanced Energy and Power Program (APEP) at the University of California, Irvine (UCI) under DE-FOA-0000997. The purpose for creating such a specification is to facilitate the deployment of microgrids in pursuit of greater grid resiliency by reducing the up-front cost and effort of engineering of microgrid controllers and improving the interoperability of components and future enhancements. In accordance with the requirements of the FOA the GMC provides for:

1) Seamless islanding and reconnection of the microgrid,
2) Efficient, reliable, and resilient operation of the microgrid, with the required power quality, whether islanded or grid-connected,
3) The ability to provide existing and future ancillary services to the larger grid,
4) Capability for the microgrid to serve the resiliency needs of participating communities,
5) Communication with the electric grid utility as a single controllable entity, and
6) Increased reliability, efficiency and reduced emissions.

This specification is organized in a manner intended to complement the structure of IEEE 2030.7 and 2030.8 standards which are under development by the P2030.7 and P2030.8 Working Groups. The functions outlined in this document have been implemented with a commercial power control software product for UCI Microgrid in order to test the applicability and utility of the specification. The scope of this document does not include hardware equipment specifications.

Any microgrid control system conforming to these specifications shall:

1. Provide configurable "fill-in the blanks" forms for one Master Microgrid Controller (MMC) and any number of device level Load Controller (LC), Generation Controller (GC), Storage Controller (SC), Breaker Controller (BC), and nested MMC modules.
2. Implement in the MMC the core functions of Transition and Dispatch in accordance with IEEE 2030.7
3. Test the core functions of Transition (Connect/Disconnect) in accordance with IEEE 2030.8

4. Provide a standard model for higher level functions to access the services of the core functions rather than bypassing these core functions.
5. Provide MMC modules which present the microgrid to the larger grid as a single controllable source of positive and negative real and reactive power(+/-PQ), that is, as either a grid feeding or grid supporting source.
    a. The MMC shall accept time schedule orders for +/-PQ.
    b. The MMC shall accept +/-PQ as a function of frequency and/or voltage
6. The MMC and GMC modules shall enable grid forming modes of operation for both islanded and connected operation. This means the microgrid can act as a grid feeding, grid supporting, or grid forming power source with respect to the larger grid, proving the physical assets can support these modes.

2 Background

In this section, a brief background on microgrids, and microgrid development is provided along with a discussion about what type of microgrids (or DER) can this specification be applied to, and what the minimum requirements are.

2.1 Motivation for Building Microgrids

Motivations of building a microgrid include: increased reliability, economic benefits (especially benefits of self-generation, peak shaving), integration and management of intermittent renewable resources, and environmental benefits including reduced greenhouse gas and criteria pollutant emissions.

After super-storm Sandy in October 2012, microgrids were recognized at the national level as the key component in increasing the reliability of the grid, building resilient communities, and facilitating public safety. A key aspect of a microgrid is that it can disconnect from the grid and support, at a minimum, critical loads. Islanded mode conditions can be substantially different from those of the grid-connected scenario. In the event of islanded operation, the grid reference becomes unavailable and local voltages and frequency become much more sensitive to generation and load fluctuations. A microgrid controller is required for seamless islanding, proper system operation during islanding, and seamless reconnection to the utility grid. ("Seamless islanding" can be defined by the microgrid owner/operator. For the purpose of this document, it is defined as transition from grid-connected to islanded mode with minimum loss of critical load and without losing the power to the microgrid entirely.)

A principal purpose of the controller is to transition the system into islanded-mode operation when appropriate and to ensure system stability by balancing load and generation during the islanded mode operation.

During the vast majority of time, the microgrid is grid connected. Under this condition, the controller should ideally (1) be responsible for economic dispatch and system optimization of efficiency, emissions, service to the customer, and (2) provide ancillary services to support utility grid economy, reliability, and resiliency.

2.2 Examples of Common Microgrids

Some examples of existing microgrid projects/demonstrations are:

- Consortium for Electric Reliability Solutions (CERTS): The CERTS microgrid demonstration test bed is located in Columbus, Ohio. The test bed includes three 60kW inverter coupled generators and a static switch. Two island capable feeder circuits connect loads to generation. This project addresses microgrid control using a decentralized control scheme. While a communications system is in place to allow for operations optimization, the CERTS microgrid has no master controller, and rather utilizes a peer to peer connection with local devices acting autonomously. A shallow droop setting and very high speed grid interconnection switch are the keys to this approach.
- NREL: The National Renewable Energy Laboratory tests various switch-gear and other smart grid technologies.
- New Energy and Industrial Technology Development Organization (NEDO): Overseas, NEDO in Japan is supporting several microgrid demonstration projects. The first of these, the Aichi project, a component of the Regional Power Grids with Renewable Resources Project, was established in 2006. The Aichi project demonstrated load-generation balancing to within 3% using a variety of devices including 1.295 MW of fuel cell generation, 330 kW of PV, and a sodium sulfur battery energy storage system. Japan is heavily involved in microgrid research and demonstration projects, setting targets including a 30% clean energy goal by 2030.

- European Union Microgrids Research Project: Two major microgrid projects have been developed, led by the National Technical University of Athens in collaboration with 4 EU countries. The project aims to study the operation of a microgrid to increase penetration of renewable generation resources, study the microgrid connected and islanded mode operations, develop control strategies to ensure efficient, reliable, and economic operation, define appropriate protection and grounding polices, identify and develop the required communications infrastructure and protocols, and simulate and demonstrate microgrid operations. Other projects include the LABIEN microgrid in Spain and the Kythnos Microgrid.
- Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory is engaged in several microgrid projects. The LBNL-Los Angeles Air Force Base Vehicle to Grid Building Integration Project consists of the grid integration of a 40-vehicle 100% plug-in electric vehicle fleet and respective bidirectional level 2 charging stations. The Santa Rita Jail project funded by the DOE has resulted in one of the most energy efficient jails in the U.S. The 4,500 inmate facility has a peak electrical demand of 3.0 MW and has a 1.2 MW PV system. The facility also contains a 1 MW molten carbonate fuel cell with a heat recovery system that provides pre-heating of hot water. A total of 6 MW-hr of lithium-ion battery storage is installed at the jail in collaboration with the Consortium for Electric Reliability Technology Solutions (CERTS), which allows the jail to disconnect from the grid and operate as an islanded microgrid for extended period of time.

The microgrid controllers developed under these programs are specific to one microgrid. In contrast, the GMC includes generic modules designed for adaptation to microgrids of various sizes and comprised of various resources.

At a minimum, the GMC should be able to communicate with the grid, generating resources, and controllable loads, building energy management system, and energy storage if they are available on the microgrid. Examples of common microgrids are:

(1) Conventional generation or Combined heat and power + controllable loads
(2) Conventional generation or Combined heat and power + controllable loads + energy storage
(3) Renewable resources + energy storage
(4) Renewable resources + energy storage+ controllable loads

2.3 Excluded from Definition

Excluded from this specification is any system with more than one point of common coupling with the grid. Also depending on the design and architecture of the microgrid some functionalities might not be available. For example to enable "seamless" transition, the microgrid needs at a minimum controllable loads or energy storage and with only generating resources, seamless islanding might not be achievable in all circumstances.

3 GMC Overview

A microgrid is defined by the DOE as "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 mode."

A chief goal of any microgrid control system is to present the microgrid to the larger grid as such a single controllable entity. This means that the larger grid need have no knowledge of the components and inner working of the microgrid. If the larger grid, for example, requests an additional real power output of X kW, the control system can achieve this by reducing load, increasing generation, or discharging storage. The larger grid should be indifferent to how the microgrid achieved the desired result.

This decoupling of decision making is considered one of the strengths of a microgrid. The microgrid owner has knowledge of the microgrid assets, the processes these assets support, and the economics of different ways of achieving the same result. The operator of the larger grid need have no involvement in such decision making.

A microgrid control system may be disaggregated from at least three different perspectives, the functional, physical, and time of action views.

3.1 The Functional View

The functional view of a microgrid controller, or better a microgrid control system, is an abstract view independent of the number or arrangement of physical control "boxes." The functional view says nothing about whether the actual control system is implemented in a hierarchical or peer-to-peer manner. It begins with identifying all of the functions a microgrid control system must accomplish and organizing them in some fashion. Most commonly this is done by grouping the functions into a number of hierarchical groups in layers.

For purposes of describing the GMC, the functions that must or can be performed in a microgrid control system are grouped into three levels of functions as depicted in Figure 1.

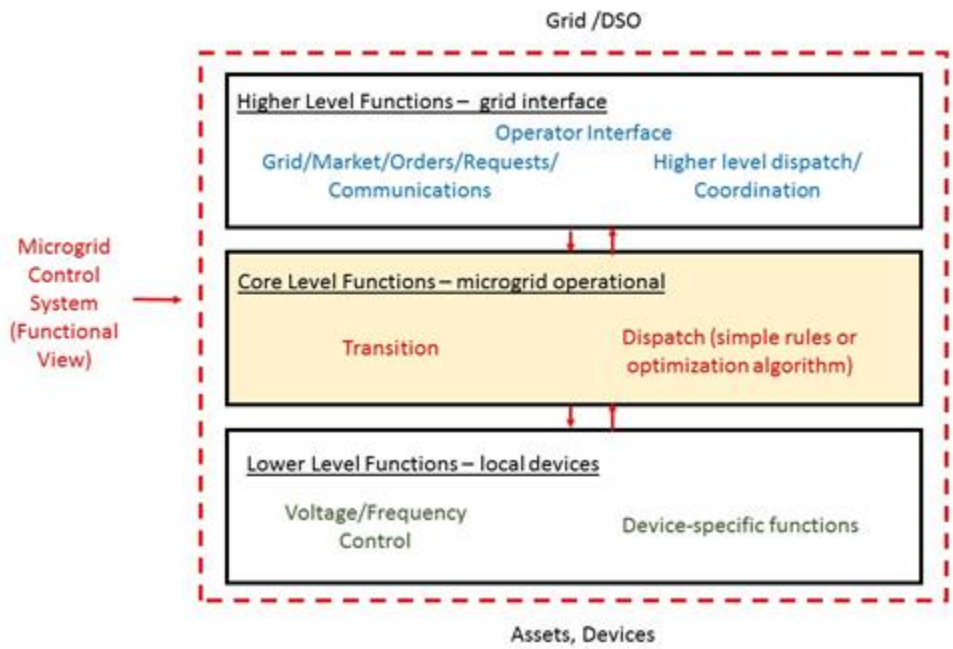

Figure 1. Levels of control

As stated, this depiction is abstract and the functions identified may be realized in any combination of physical controllers, but the lower level functions are typically realized by such things as generator governors, automatic voltage regulators (AVRs), on-load tap changes, capacitor switches, and variable frequency drives (VFDs). The core and higher level functions are typically implemented in a dedicated microgrid controller which supervises the assets and provides the single point of control for the overall system as seen from outside.

This three layer model may be considered analogous to a computer, with applications at the highest level, the operating system as core, and device drivers as the lower level functions.

3.1.1 The Core Functions

The two core functions of Connect/Disconnect (Transition) and Dispatch depicted in Figure 1 are the subject of IEEE P2030.7 and P2030.8 and are generally considered the minimum additional functionality above the device or asset level necessary to constitute a microgrid.

The *Transition (or Connect/Disconnect)* function includes (1) unplanned islanding, (2) planned islanding, (3) reconnection, and possibly (4) black start. It detects an unplanned island and orders the dispatch function to execute the unplanned islanding dispatch order. The Transition function also accesses services from the Dispatch function to achieve real and reactive power balancing necessary for successful planned islanding and reconnection.

The *Dispatch* function includes the dispatching of microgrid assets and providing them with appropriate setpoints. It includes dispatching while connected and while islanded. The Dispatch function generates and executes dispatch orders to particular microgrid assets in accordance with dispatch rules, which can be as simple as up and down regulation requirements coupled with a priority table or as sophisticated as a value added optimization engine. It calculates a reliability oriented "Emergency Dispatch Order (EDO)" for execution upon unplanned islanding events and updates this order continuously. To perform its functions, the Dispatch function also receives microgrid system state information and maintains a current state of the system database for its own calculations and those of any higher level functions such as a dispatch optimizer.

3.2 The Physical View

In the physical view we consider the actual control "boxes" that comprise the control system and their interconnections. This begins with controls inherent to the components of a microgrid such as generator governors, automatic voltage regulators, variable frequency drives, motor and lighting contactors and sensors. Above these may or may not be local controllers which aggregate some, but not all, of the component controllers. Examples of these include PLCs that control a group of generators and building energy management systems that control numerous lighting and HVAC loads in a building.

What is commonly thought of as a microgrid controller may then exist in a dedicated controller with connections to both end devices and the local controllers. This microgrid controller may be limited to the core transition and dispatch functions or may include sophisticated higher level functionality such as optimization, forecasting, and grid market interaction.

Figure 2 illustrates some different options for packaging and grouping control system functions into various control boxes.

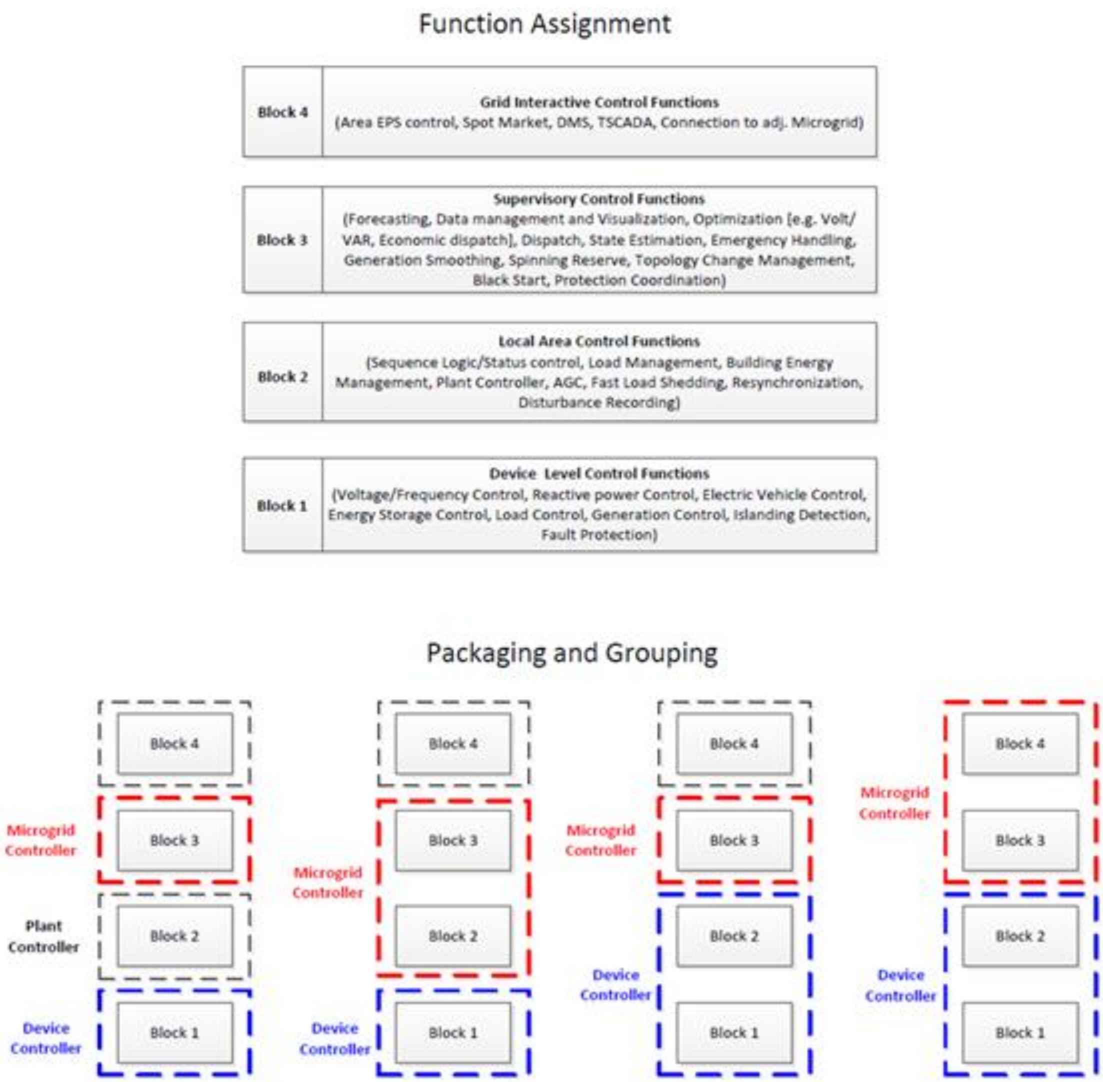

Figure 2 Physical View of Microgrid Controllers

There are more options for these physical groupings. Distributed control architectures can be used in which there is no apparent physical hierarchy. It is also possible to locate some functions in "the cloud," especially the highest level ones.

3.3 The Time of Action View

Utilities traditionally speak of frequency response to a disturbance in terms of primary, secondary and tertiary control response. Primary response consists of physical inertia and local generator droop governor behavior, and acts to arrest the frequency excursion. Secondary response consists of the Area Generation Control (AGC) acting on the Area Control Error (ACE) signal to adjust the output of selected generators to return the system to normal frequency. Tertiary response involves the economic re-dispatch of resources which has traditionally been a human operator function. Microgrid control system specialists have borrowed from this terminology to describe the time scale at which various parts of the system are expected to respond. This is depicted in Figure 3.

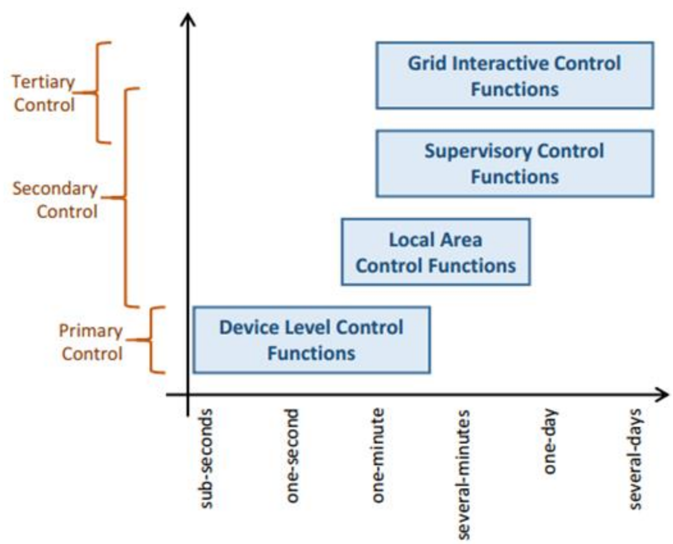

Figure 3 Control Elements Time of Action

This depiction shows that fast response is only required of functions typically located at the device control level, such as generator governors. Supervisory and grid interaction functions do not have to meet similar time constraints. This relaxes time performance requirements for these higher level control elements and at least some of the communications.

4 The GMC Functional Specifications

Building on the framework developed by the P2030.7 and P2030.8 Working Groups, APEP and its partners have developed a Generic Microgrid Controller (GMC) specification presented herein. The idea behind this specification is to encourage a common framework for microgrid controllers across the industry. Controllers developed in accordance with this specification will provide the following benefits:

1. The controllable assets of the microgrid can be specified by adding "fill-in the blanks" forms.
    a. This reduces the engineering effort required to implement a microgrid control system.
    b. This allows the Master Microgrid Controller (MMC) to be the same for most microgrids.
2. The MMC will present the microgrid as a single controllable entity.
    a. This facilitates nesting of MMCs.
    b. This helps standardize the interconnection of microgrids to utility grids.
    c. This allows interoperability of higher level functions from different manufacturers.

These benefits are intended to lower the barriers to more widespread deployments of microgrids resulting in: (1) improved electric power system resilience, and (2) increased deployment of distributed renewable resources by adding the value of power supply assurance. It also provides an upgrade-friendly architecture where improved higher level functions can rely on a standard interface to the core functions in much the same way applications can rely on an operating system.

In practice, the GMC specification could be included as the core of a particular purchase specification with additional customer requirements added as higher level functionality.

This section describes the architecture of the GMC. The GMC is partitioned into one centralized class of components, the Master Microgrid Controller (MMC) and five classes of distributed components: Generation Controllers (GC), Storage Controllers (SC), Load Controllers (LC), Breaker Controllers (BC), and a subordinate MMC to enable nesting of microgrids. These elements are responsible for overall coordination of the microgrid, control of distributed generation devices such as diesel generators and PV, control of storage devices such as batteries, control of dispatchable loads, control of breakers and switchgear, and control of nested microgrids (nanogrids) respectively.

Figure 4 shows the physical architecture and overall framework of the GMC. The physical assets of the microgrid are shown in blue and consist of an intertie breaker, one or more load elements, one or more generator elements, zero or more storage elements, and zero or more nested microgrids. For each dispatchable element there is an asset level control module. Each of these modules has a "fill-in the blanks" form to describe the asset to the MMC. The functionality of these modules correspond to the lower level functions shown in the previous figure.

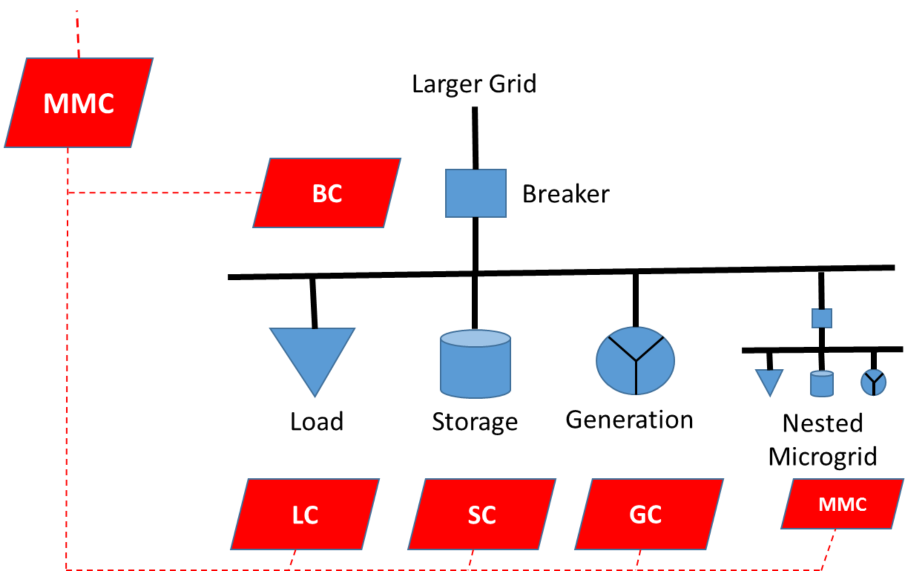

Figure 4 GMC Framework

4.1 Master Microgrid Controller (MMC)

The MMC 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 possibly the supply of ancillary services. The MMC presents the microgrid to the larger grid (or microgrid) as a single controllable entity.

The MMC contains the Transition and Dispatch Function as a minimum, and may contain additional higher level functions as value added features which are described in Chapter 5.

The MMC similarly has a “fill-in the blanks” form to describe the overall microgrid as a single controllable entity to communicate with the larger grid to which it is connected. The microgrid is presented to the larger grid as a source of positive or negative real and reactive power which can operate in a grid feeding, grid supporting, or grid forming mode.

The MMC incorporates the P2030.7 core functions of Transition (Connect/Disconnect) and Dispatch, and includes the higher level functions as value added options as shown in Figure 5. The dispatch function computes its dispatch order from a dispatch rule. In the simplest case this rule is static and set up by the operator in the beginning. A value added dispatch optimizer engine would be considered a higher level function and optimizes dispatch by editing the dispatch rule in real time. This modularizes the optimizer and dispatch functions, making modifications and upgrades of the optimizer easier.

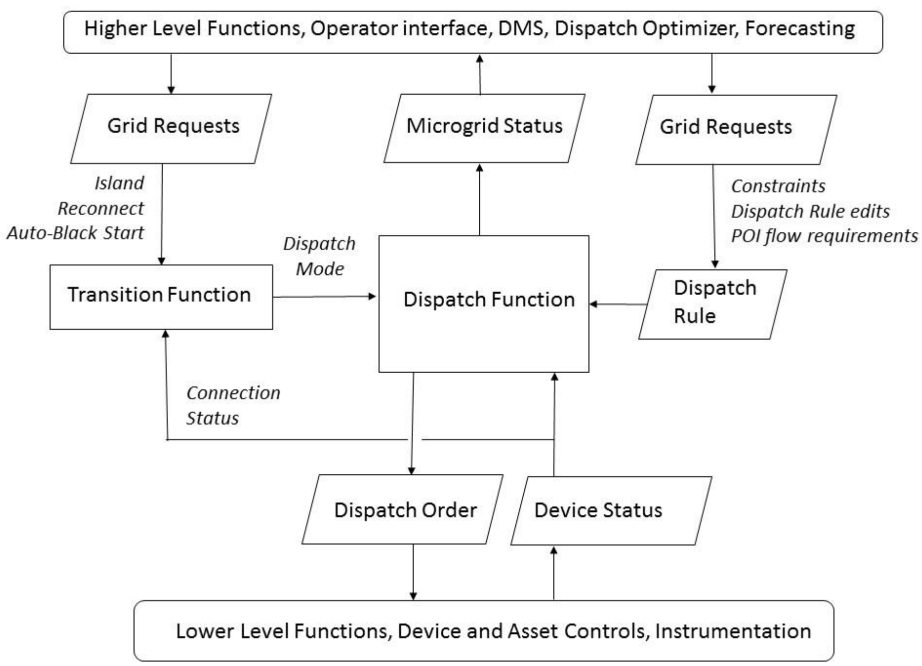

Figure 5. MMC core functions

The MMC’s dispatch function coordinates microgrid assets for optimal and stable operation during each of six possible dispatch operating modes:

SS1 - grid connected steady state

SS2 - island steady state

T1 - unplanned islanding

T2 - planned islanding

T3 - reconnection

T4 - black start

The mode in which the dispatch function in the MMC operates is controlled by the logic of the transition function. The dispatch function accesses and implements the dispatch rules for each of these dispatch modes.

4.1.1 Operator Control

Operators and higher level functions control the microgrid by providing inputs to the transition function and the dispatch rule. Those inputs as shown in Figure 5 are as follows:

- Inputs to the Transition Function
  - Planned Island Request
  - Reconnect Request
  - Automatic Black Start Enabled
- Inputs to the Dispatch Rule
  - Constraints on dispatch
    - Constrain steady state connected dispatch to ensure successful unplanned islanding
    - Constrain the dispatch of any particular physical asset
    - Physical constraints of the system (such as generator ramp rates)
    - Emissions constraint (depending on the location of the microgrid)
    - Fuel availability
  - Dispatch rule edits to change the priorities and logic of the dispatch rules for any of the dispatch modes. An example is scheduled maintenance of the generating units.
  - PCC flow requirements. A type of constraint reflecting the desired microgrid power exchange at the PCC. In general this can be P and Q as a function of time, voltage and frequency. This is potentially impacted by the interconnection agreement between the microgrid and the utility.

4.1.2 Transition Function

The controller utilizes a rule based algorithm to achieve all transitions, including reconnection, seamless planned transition into islanded mode, and seamless unplanned islanding if the microgrid resources physically allow it.

The transition function executes the logic shown below and sets the dispatch operating mode of the Dispatch function.

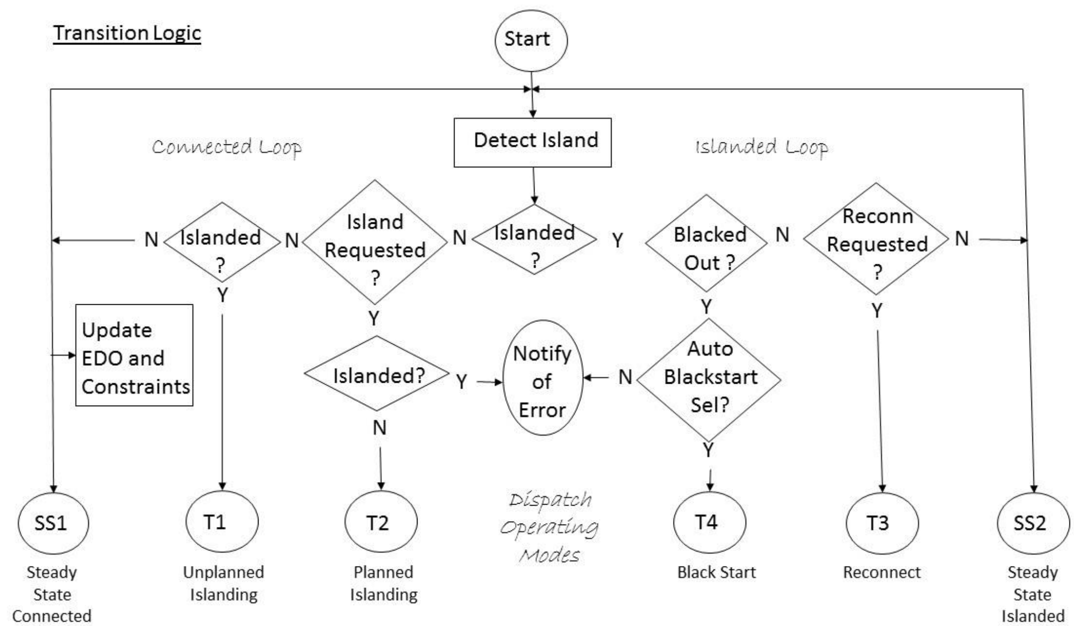

Figure 6. Transition logic

The Transition function thus runs in one of two loops, connected state or islanded state, and sets the Dispatch function to operate in the appropriate steady state dispatch operating mode for the state of the microgrid. Upon detecting a transition event it changes the dispatch operating mode of the Dispatch Function.

4.1.3 Dispatch Rule

The six default dispatch mode rules used by the Dispatch Function to calculate its dispatch order are described below. Asset parameters monitored and/or controlled by the MMC are defined in Table 1. These rules may be edited by the microgrid owner/operator to reflect additional priorities as desired.

Table 1. Parameters controlled/monitored by the MMC

Symbol	Description	Comments
I	Isochronous Mode	A grid forming mode of constant frequency and/or voltage
D	Droop Mode	A grid forming mode where F/V droop as P/Q increases
Fd	Grid Feed Mode	P/Q output independent of F/V
Spt	Grid Support Mode	P/Q output dependent on F/V
G	Present Total Generation	Sum of all generator outputs
L	Present Total Load	Sum of all loads
LCrit	Critical Load	Must be able to supply at all times
GBig	Largest single gen output	Current output, not max output
LA	Max anticipated load	
LOL	Max potential load loss	
MMax	Maximum Motor Starting Amps	Max starting amp of any motor not blocked
MStart	Maximum Motor Starting	Total momentary G and S amps available with V >= 0.8 P.U.
S	Storage power	Charge or discharge kW
SOC	State of charge	Of all storage resources in kWh
DR	Demand Response	Load available to shed
BR	Breaking Resistor	Load available to add to mitigate LOL
U	Up Reserve	Additional power available from online generation
D	Down Reserve	Down power available from online generation
U-1	N-1 Up Reserve	Up reserve after trip of generator carrying largest current load
UIC	Unplanned Island Constraints	Dispatch limits while connected to support unplanned island
ITR	Intertie Request	P/Q flow at POI requested by grid and/or operator
ITC	Intertie Constraints	Interconnection requirements, e.g., anti-islanding, ride-through

SS1. Connected steady state rule

- Adjust generation and load per priority table such that P, Q flow at Point of Interconnection (POI) match that requested by operator and/or grid subject to unplanned islanding contingency constraints
  - L-G-S-DR-MMC >= UIC, Sufficient resources to carry load upon unplanned islanding.
  - I=0, No generators in isochronous mode while paralleled.
  - D >= 1, At least one grid forming generator in droop mode while paralleled to support unplanned island.
- Calculate and update an EDO to be used immediately upon initiation of T1 mode. The calculation of the EDO is coordinated with the SS1 dispatch order by knowing what has already been dispatched. The SS1 dispatch order is in turn affected by the presence or absence of a constraint to be able to execute a seamless transition during an unplanned islanding event. If this constraint exists, the SS1 will, for example, maintain a higher percentage of self-generation and manage and provide setpoints to microgrid assets enabling them to respond autonomously to the unplanned island event. In this way the GMC can take maximum advantage of intelligence imbedded in the asset controllers and supplement that (or back it up) with direct asset control using the EDO.
  - <u>Example</u>: A storage controller (SC) has the ability to sense frequency and change mode on its own. SS1 sets the SC to operate in PV smoothing mode, but to autonomously switch to proportional power frequency support mode upon sensing frequency above or below certain setpoints. The Dispatch Function takes this into account when preparing its EDO.
  - <u>Example</u>: A building on the microgrid is equipped with building energy management. The amount of load that needs to be shed from that building upon imitation of T1 mode is determined in EDO and sent to the BMS. In case of T1 the BMS acts autonomously based on the EDO setpoints.
  - <u>Example</u>: A load to be shed by the Dispatch function upon unplanned islanding is controlled by a breaker with a shunt trip coil. The dispatch function will directly trip the breaker upon execution of the EDO.

  - Example: An inverter can operate in either grid feeding mode or grid forming droop mode, but cannot change mode autonomously. SS1 sets the inverter to operate in grid feeding mode. Upon execution of the EDO the Dispatch Function directly commands the inverter to shift to grid forming mode.

SS2. Islanded steady state rule

- Dispatch load and generation such that frequency and voltage are maintained within acceptable limits.
  - I<=1, I+D >=1, At least one grid forming generator but no more than one isochronous generator.
- Coordinated dispatch of generation resources
  - Act as AGC to restore frequency in absence of or failure of any isochronous generator to do so.
  - Prioritize generation in accordance with dispatch rule.
  - Balance loading of generation in accordance with dispatch rule.
  - Prioritize serving of critical loads and reliability over economics
- Ensure available resources (generation, storage, and demand response) are dispatched to accommodate design up and down regulation; i.e., that largest anticipated load or generation changes and motor starting events can be accommodated by existing dispatched resources.
  - U >= LA-L, Dispatched generators have up reserve for anticipated load increase.
  - U+S+DR >= LCrit, Support critical load, (if SOC <SOC_Min then S=0)
  - U-1+S+DR >= GBig, Survive loss of generator carrying largest amount of load.
  - D+S+BR >= LOL, Survive maximum loss of load event. (if SOC>SOC_Max then S=0)
  - MStart >= MMax, Ability to start largest motor which is not blocked from starting. This may be satisfied by blocking the starting of any motor too big to start.

T1. Transition from connected to unplanned island rule. This utilizes the Emergency Dispatch Order (EDO) which is calculated and continuously updated as conditions change by the Dispatch Function while in SS1 dispatch mode.

- Execute load, storage, nested microgrid and generation dispatch in EDO when notified of unplanned island by Transition function.
  - Includes change of protection setting groups and other operating modes as necessary.
- Shift to SS2 dispatch operating mode.
  - EDO is a pre-calculated dispatch order necessary to satisfy the requirements of SS2, that is, to transition from SS1 to SS2.

T2. Transition from connected to planned island

- Dispatch assets so as to match load and generation, resulting in zero exchange at PCC.
- Ensure dispatched assets include design up and down regulation margin.
- Change generation resource modes to ensure one resource operating in grid-forming droop mode (not isochronous) and other resources in grid feeding or grid supporting modes.
- Open PCC breaker.
- Change protection settings group and other operating modes as necessary.
- Shift to SS2 dispatch operating mode. (Isochronous mode for one generator permitted but not required)

T3. Transition from islanded to connected

- If necessary, change grid forming resource from isochronous to droop mode for parallel operation with grid.
- Adjust frequency, voltage and phase to within specified paralleling limits.
- Close PCC breaker.
- Change protect settings group if necessary
- Shift to SS1 dispatch operating mode. (Up and down regulation, LOL and motor starting contingencies not required since grid is presumed able to support these events)

T4. Transition from islanded blackout to islanded steady state

- Clear load busses of clearable loads.
- Start black start generation resource in grid forming mode and energize highest priority load bus(es).

- Sequence load and generation on by black start priority table. Sequencing allows time to start any large motors. These generators are to be in droop, grid feeding or grid supporting modes.
- Shift to SS2 dispatch operating mode.

4.1.3.1 AGC and ACE in the GMC Dispatch Function

As discussed in Section 3.3, the utility terms AGC and ACE are sometimes used in discussing microgrid control systems. There are several differences between utility systems and microgrids which makes this confusing and perhaps inappropriate: (1) Utility systems have several points of interchange with neighboring utilities and need to maintain scheduled power flows across these interties. Microgrids operate with a single point of interconnection, usually to a much larger system, and may or may not have scheduled flows, (2) utility systems typically have many internal generators to coordinate while microgrids typically have few or even only one, and (3) utilities must coordinate their joint effect on the frequency of the larger interconnection while microgrids either follow the larger grid frequency when connected or regulate their own frequency when islanded.

Nevertheless, there are certain duties located in the dispatch function which are analogous to the utility AGC:

1. Power flows at the PCC may have to be regulated to defined values for particular periods of time while internal load and generation are varying. If the PCC flows are to be regulated, the MMC's dispatch function must supervise the internal assets. It may, for example, regulate the output of a particular generator up and down to keep PCC flow constant in spite of variations in internal load.
2. Load sharing between internal generators may need to be supervised to meet requirements of the dispatch rule with respect to security, contingency margins, emissions and economy of operation.
3. If a given microgrid design involves all generators operating in droop mode with none in isochronous mode, islanded frequency will naturally vary with load. The MMC's dispatch function would then have to re-dispatch the bias setpoints of these generators to maintain frequency within defined limits.

4.1.4 Incorporating Optional Higher Level Functions

A microgrid control system may optionally include many higher level functions such as optimal dispatch and market interaction. These functions may be included in a generic microgrid controller's MMC provided they implement their control of the microgrid assets through the MMC's transition and dispatch function as described in section 4.1.1.

A further discussion of some of these higher level functions is provided in Section 5 "Other Functions."

The MMC receives asset state information such as voltage, power levels and status indication and uses this information in accordance with its dispatch rule to compute a dispatch order, which is a set of commands sent to the assets.

The dispatch order controls assets by turning individual assets on or off, by changing their operating modes, and by providing them with appropriate setpoints. It does not take the place of local asset controllers such as governors or voltage regulators.

From this discussion of the Transition and Dispatch functions, the "fill-in the blanks" for the Asset Controllers follow. Each controller's form is shown for a given "i^{th}" asset. Each asset discretely dispatchable by the MMC must have its own controller even if it is reached through an intermediate controller in physical implementation.

4.1.5 Asset Level Controllers - General

Asset level controllers are to the MMC as device drivers are to an operating system. They all present themselves to the MMC as abstract device, with the GC looking the same for all types of physical generators. They describe themselves to the MMC in terms of the parameters the MMC needs to know. They translate between these abstract quantities and the physical quantities used by the local controls of the physical asset as shown in Figure 7.

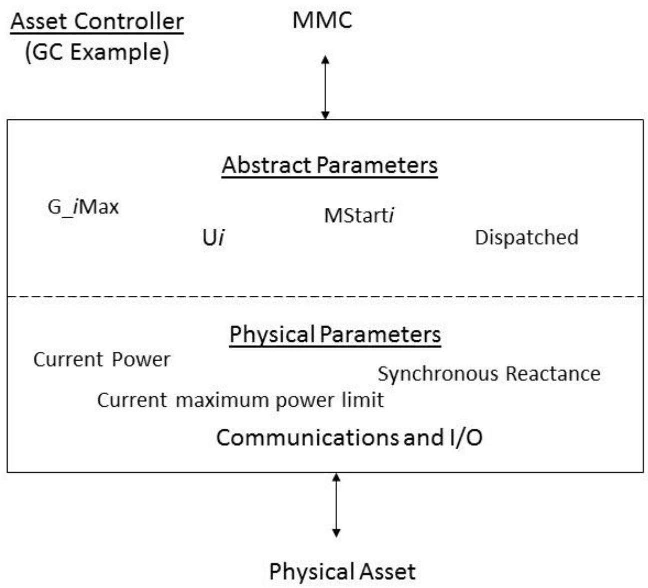

Figure 7Asset Controller

4.1.6 Breaker Controller

Breaker controllers monitor and actuate microgrid breakers. Breaker controller functions may be implemented natively on smart breaker devices, or on an industrial programmable logic controller if native implementation of control functions is not possible and necessary devices inputs are available.

Breaker controllers will accept the following setpoints from the Microgrid Master Controller:

1) Low latency islanded mode detection signal
2) Breaker Control Signal

Breaker controllers is capable of enumerating a unique device identifier and broadcasting the *breaker status* to other GMC components:

Supported devices include Point of Common Coupling, breakers, switches, and disconnects.

A summary is provided in Table 2.

Table 2. BC

BC		Only one POI Breaker
POI Breaker		
Symbol	**Description**	**Comments**
POI	Open or Closed	
POIX	Tripped	If opened by fault protection
POIP	Power flow at POI	
POIQ	Reactive Power Flow at POI	

BC_*i*		Any internal (non-POI) breaker, switch or disconnect
Non-POI Breaker_*i*		
Symbol	**Description**	**Comments**
BKR_*i*	Open or Closed	
BKRX_*i*	Tripped	If opened by fault protection
BKRP_*i*	Power flow at BKR_*i*	
BKRQ_*i*	Reactive Power Flow at BKR_*i*	

4.1.7 Generation Controller

Generation controllers monitor and actuate microgrid distributed generation resources. Generation controller functions may be implemented natively on generation devices, or on an industrial programmable logic controller if native implementation of control functions is not possible and necessary devices inputs are available.

Generation controllers will accept the following setpoints from the Master Microgrid Controller:

1) Low latency islanded mode detection signal for governor mode change
2) Control mode commands from the MMC: Grid forming (isochronous, droop), grid supporting, and grid feeding
3) Real Power Setpoint
4) Reactive Power Setpoint
5) Voltage Setpoint

Generation controllers will be capable of enumerating a unique device identifier and broadcasting the following real-time values to the MMC:

1) Real power output, reactive power output, power factor output
2) Power quality (harmonic distortion)
3) Local bus voltage, current
4) Generation capability curves, percent loading, fuel utilization, fuel remaining
5) Device ratings and self-describing information

Supported devices include but are not limited to:

1) Diesel Generators
2) Wind Turbines
3) Photovoltaic Arrays / Inverters
4) Fuel Cells
5) Microturbines
6) Gas Turbines
7) With and without combined heat and power (CHP)

A summary is provided in Table 3.

Table 3. GC

GC_*i*		The "i^{th}" GC
Generator *i*		
Symbol	**Description**	**Comments**
Dispatched	Yes or No	
I, D, Fd, Spt	Governor and AVR control mode	
G*i*	Current P and Q of this i^{th} generator	G = Σ G*i*
G*i*_Max	Current maximum P, Q available for generator *i*	
G*i*_Min	Current minimum P, Q available for generator *i*	
U*i*	Up Reserve of generator *i*	U*i* = G*i*_Max - G*i*
D*i*	Down Reserve of generator *I* without tripping	D*i* = G*i* – G*i*_Min
MStart*i*	Motor starting current available from generator *I* = current above full load current with terminal voltage >= 0.8 P.U.	

4.1.8 Load Controller

Load controllers monitor and actuate microgrid loads. Load controller functions may be implemented natively on smart load devices, or on an industrial programmable logic controller if native implementation of control functions is not possible and necessary devices inputs are available.

Load controllers will accept the following setpoints from the Master Microgrid Controller:

1) Low latency islanded mode detection signal
2) Dispatch signal

Load controllers are capable of enumerating a unique device identifier and broadcasting the following real-time values to other GMC components:

1) Real power, reactive power, power factor, power quality (harmonic distortion)
2) Voltage, current
3) Demand response capabilities (shed capability vs. time windows)

Supported devices include:

1) Controllable Loads (VFD's, lighting, elevators, air handlers)
2) Monitored
3) On/Off Loads

A summary is provided in Table 4.

Table 4. LC

LC_*i*		The "i^{th}" LC
Load *i*		
Symbol	**Description**	**Comments**
Dispatched	Yes or No	
Lcrit*i*	Yes or No. Is load *I* critical?	
L*i*	Current P and Q of this i^{th} load	L = Σ L*i*
LA*i*	Max anticipated load for load *i*	
LOL*i*	Max potential load loss for load *i*	
MMax*i*	Maximum Motor Starting Amps at load *i*	Max starting amp of any motor not blocked at load *i*

4.1.9 Storage Controller

Storage controllers monitor and actuate microgrid storage devices. Storage controller functions may be implemented natively on smart storage devices, or on an industrial programmable logic controller if native implementation of control functions is not possible and necessary devices inputs are available.

Storage controllers will accept the following setpoints from the Master Microgrid Controller:

1) Low latency islanded mode detection signal to change operation mode
2) Control mode: Grid forming (isochronous, droop) , grid supporting, grid, grid feeding
3) Real Power output setpoint, reactive power output setpoint
4) Real Power input setpoint, reactive power input setpoint

Storage controllers will be capable enumerating a unique device identifier and broadcasting the following real-time values to other GMC components:

1) Real power, reactive power, power factor, power quality (harmonic distortion)
2) Voltage, current
3) Storage capacity (current, maximum). Power output maximum
4) Other operating conditions such as state of charge

Supported devices include but are not limited to:

1) Flywheels
2) Batteries
3) Thermal energy storage devices
4) Compressed air
5) Pumped storage
6) Hydrogen storage

A summary is provided in Table 5.

Table 5. SC

SC_*i*		The "i^{th}" SC
Battery *i*		
Symbol	**Description**	**Comments**
Dispatched	Yes or No	
I, D, Fd, Spt	Governor and AVR control mode	
S*i*	Maximum P and Q of this i^{th} generator	S = Σ S*i*
SOC*i*	kWh available	
SOC_Max*i*	Maximum SOC for this storage element	
SOC_Min*i*	Minimum SOC for this storage element	
MStart*i*	Motor starting current available from storage inverter *i* = current above full load current with terminal voltage >= 0.8 P.U.	

4.1.10 Nested microgrids

A microgrid can contain a smaller microgrid (nanogrid) as an asset. This smaller microgrid includes an MMC which is congruent with the MMC of the larger microgrid.

Master Microgrid Controllers monitor and actuate microgrid assets and present the microgrid (or nanogrid) as a single controllable entity to the grid (or larger microgrid).

MMC of the smaller microgrid accepts the following setpoints from the Master Microgrid Controller:

1) Low latency islanded mode detection signal to change operation mode
2) Control mode: Grid forming (isochronous, droop) , grid supporting, grid, grid feeding
3) Real Power output setpoint, reactive power output setpoint

MMC will be able to broadcast the following real-time values to the larger microgrid (or grid):

1) Real power, reactive power, power factor, power quality (harmonic distortion), and energy capabilities
2) Voltage, current

Supported devices include all microgrids (and nanogrids). A summary is provided in Table 6.

Table 6. Nested MMC

MMC_*i*		The "i^{th}" MMC
Microgrid *i*		
Symbol	**Description**	**Comments**
Fd, Spt	Governor and AVR control mode	
MMC*i*	Current P and Q of this i^{th} MMC POI	Contributes to G or L. Positive for G.
MMC*i*_Max	Current maximum P, Q dispatchable	Generation at POI is positive
MMC*i*_Min	Current minimum P, Q dispatchable	Minimum can be negative if acting as load at POI
MMCU*i*	Up Reserve of MMC *i*	MMCU*i* = MMC*i*_Max - MMC*i*
MMCD*i*	Down Reserve of MMC *i*	MMCD*i* = MMC*i* – MMC*i*_Min
MStart*i*	Motor starting current available from MMC*i* = current above full load current with terminal voltage >= 0.8 P.U.	

4.2 Communication

In general, communications are an implementation issue for microgrid control systems and many choices are available for controllers conforming to this specification. However, the GMC has been designed to place as little reliance on the speed of communications as possible so that it can be implemented in situations where slower communications may be employed.

This is achieved by the layered architecture of the GMC. While low level functions such as generator governor control must operate in real time, there is more time for transition and dispatch functions. Planned islanding and reconnection can proceed methodically, and routine dispatch during steady state conditions likewise. This dispatch brings resources on line to ensure that these resources, with their autonomous features, are adequate for anticipated load changes and contingencies where timely response is of the essence.

As for unplanned islanding, an Emergency Dispatch Order is created and continuously updated by for immediate use by the dispatch function upon island detection. Additionally, constraints on the dispatch function are determined to ensure the dispatch order in effect prior to any unplanned islanding event includes resources and settings necessary to successfully transition in combination with the Emergency Dispatch Order, provided this constraint is elected by the operator. These constraints might include, for example, the requirement for at least one grid forming generator in droop mode to be online and for generation and load mismatch to be within a certain value.

Interface between power system network and GMC must be based on real-time messaging without use of any external files. The system shall be capable of interfacing with other enterprise systems (such as SCADA) through the use of Information Technology (IT) software modules developed based on open industry standards such as OPC, ODBC, etc. The software should have the capability to communicate simultaneously with multiple devices, including devices that are on different physical communications channels.

4.2.1 Communication Topologies

The map of communication pathways in a communication system in many ways determines the protocols to be used. Some common topologies are reviewed here. Actual systems may include combinations of these topologies.

Master/Slave

In this topology one device acts as the master and all of the other devices as slaves. There is either a point to point "star" connection from the master to the slaves, or a multipoint drop originating at the masters and dropping off at each slave. The master usually polls the slave devices one at a time for incoming data and sends commands either directly to a device or broadcasts it to many devices at once. So-called slave devices may also be able to report by exception rather than waiting for polling from the master.

This topology is common in schemes involving a host computer with Terminals and Remote Terminal Units (RTU) and is often found in legacy Supervising Control and Data Acquisition (SCADA) networks.

Local Area Network

This may be more of a peer to peer communication scheme where each device can message any other device on a local area network. Each device must have the local address, often called a Media Access Control or MAC address, of the physical devices with which it must communicate. The most common LAN protocol is Ethernet.

Wide Area Networks

Several LANs can be linked together by telecommunication links into a Wide Area Network or WAN. The LAN devices at each end of these links are called repeaters. They typically do not include the routing intelligence of routers described next, and the whole set of linked LANs appear as one LAN to the end devices.

Internetwork

Local Area Networks (LAN) are connected to each other through intelligent routers. Any device can in principle communicate with any other device on the interconnected networks using another layer of addressing called the Internet Protocol address or IP address. The routers must add another layer of routing information to get a message from a device on one LAN to a device on another LAN using these IP addresses. The routers maintain the intelligence to do this routing and keep it up to date as the internetwork configuration changes. Implementation of internetworking requires the addition of a transport layer of software to manage the communication flow and error checking and an internet layer to manage the addressing and routing of the messages. The most common software used for these purposes is TCP/IP.

Since microgrids are most commonly local systems control communication networks are commonly other than internetworked in topology. This is changing however as vendors begin to offer control via web or "cloud" services.

4.2.2 Supported Protocols

The controller should normally support the following major protocols. A more complete list is provided in Table 7.

1) 61850
2) DNP3
3) MODBUS
4) OPC & OPC-UA

Table 7. Protocols and standards

Modbus	A legacy application layer master/slave protocol often using multi-drop wired communications. Limited to one data point per message. By Modicon in 1979. Still most common multi-vendor link.
Modbus over Ethernet and TCP/IP	A scheme for transporting Modbus messages (MPAB) over a routable network.
DNP 3.0	The most common master/slave application layer protocol used by utility SCADA systems. Not limited to one data point per message.
DNP 3.0 over Ethernet and TCP/IP	A scheme for transporting DNP 3.0 messages over a routable network.
IEC 61850	A naming scheme designed for interoperable substation equipment. Designed for Ethernet.
MMS	Manufacturing Message Specification. A 61850 compliant protocol for SCADA.
GOOSE	Generic Object Oriented Substation Event. A 6185 compliant protocol for low latency protection messaging.
SMV	Sampled Measured Values. A 61850 compliant protocol for sharing measured values among related IEDs.
Web Services	Getting services from an internet based server for some connected machine. Latency is an obvious issue. May be useful for dispatch optimization. 61850 compliance is a work in progress.
IEC 60870-5-101/104	Similar to DNP 3.0. Common in Europe. 101 is serial, 104 is Ethernet.
IEC 61850-7-420	Communications standard for distributed energy resources (DER)
Physical Layer Standards	
RS-232	Oldest serial standard. 12 volt, short range.
RS-422, 485	422 is 5 volt point to point; 485 is multi-point drop often used with Modbus.
IEEE 802.3	Ethernet. RJ-45 plugs, Cat 5 or 6 twisted pair wiring or optical.
IEEE 802.11n	Latest WiFi. Wireless LAN.
IEEE 802.15	Wireless PAN (Personal Area Network). Bluetooth, Zigbee.
GSM	Global System for Mobile. A 3G cell technology common overseas.
CDMA	Code Division Multiple Access. A 3G technology used by Verizon et al in the U.S.
LTE	Long Term Evolution. A true 4G technology.

5 Other Functions

As previously mentioned the GMC has two major functions, Transition and Dispatch. These functions can be modified/expanded to enhance the capabilities of the controller. These are not required for conformity to the GMC specifications, and can be added on top of the core functions to further improve the operations of the microgrid.

5.1 Cost and Emission Analysis

Dispatch Function can be expanded to be able to calculate overall energy usage, costs, profits, and emissions from the microgrid.

1) Providing energy usage analysis and cost allocation for individual generation units, areas, and the entire microgrid.
2) Track and create energy billing reports based on user-definable energy cost functions and energy tariffs.
3) For any onsite generators and utility feeders, the software create the energy cost / profit analysis and energy production / consumption billing reports.
    a. Predict system-wide energy usage & cost allocation
    b. User-definable cost functions & generator heat rates
    c. Track energy related costs
    d. Avoid unnecessary peak demand charge & penalties such as PF penalty by updating dispatch rule
    e. Implement and track effectiveness of cost savings programs such as participating in demand response program
    f. Implement billing based on business units, buildings, or nanogrids
    g. Energy cost / profit analysis report
    h. Energy production / consumption billing
4) Calculate emissions from user-defined emission factors and heat rates associated with on-site generating units.

5.2 Load and Renewable Generation Forecasting

With the addition of this capability, the controller will be able to analyze metered and recorded data in combination with environmental data to identify trends and forecast future load as well as availability of renewable generation. A good forecast has a direct and significant impact on costly generating unit startups and shutdowns, energy purchases, managing system demand as well as scheduling system upgrades based on predicted load growth.

Adopted forecasting algorithms (such as statistical approach, or machine learning (e.g. artificial neural networks)) can be employed for short or long-term forecasts in combination with available physical models for solar and wind resources.

5.3 Ancillary Services

The economic dispatch and optimization engine discussed previously can modified to include participation in ancillary services market to generate revenue for the microgrid. To enable this, the interconnection agreements and available tariffs to access the wholesale (or retail) market should be studied and taken into account prior to implementation. GMC will

1) Determine which ancillary services specific generating units or a collection of them qualify for,
2) Calculate suitable bids (MW, $/MW and $/MWh) to be submitted to the market,
3) Communicate with the ISO (or the market operator),
4) Be capable of dispatching ancillary services at real time upon receiving a signal from the market operator
5) Update the dispatch rule when receiving a dispatch signal from the grid operator

5.4 Economic Dispatch

GMC is capable of allocating generation changes of a power system among generator units to achieve optimum economy and least cost. GMC provides guidelines for optimal electrical system operation in order to meet power requirements, steam requirements, and minimize fuel cost per generator.

The economic dispatch utilizes advanced optimal power flow algorithms in order to determine the optimal generation pattern while maintaining adequate reserve margins. Generation levels of individual units are calculated and dispatched in order to meet the load demand at minimal costs.

The economic dispatch includes the following features:

1) Generation constraints to maintain adequate online reserves
2) Incremental heat rate characteristics for each generation unit
3) Detailed nonlinear cost function modeling
4) Updating the dispatch rule to achieve minimum cost through an optimization engine

5.5 Power System Optimization

GMC is capable of allowing the operator to apply objectives and constraints to achieve an optimal power system operation. GMC provides a power system optimization mode, where recommendations are implemented based on the predefined set of objectives. This is done through "grid requests" as shown in Figure 5.

GMC utilizes optimal power flow algorithms and user-defined logics to determine the best operating settings for the system, and has the capability to assist energy consumers to automatically operate the system and minimize system losses, reduce peak load consumption, or minimize control adjustment.

5.6 Interchange Scheduling (IS)

The GMC can provide the capability to schedule energy transfer from the microgrid to the grid or another microgrid while considering wheeling, scheduling ancillary services, and financial tracking of energy transactions. The GMC can incorporate energy scheduling, transaction management, and energy cost analysis and reporting.

The interchange scheduling includes the following features:

1) Create detailed "Buy" & "Sell" transaction schedules
2) Detailed energy transaction reports for user-specified period of time
3) Evaluate energy cost
4) Extensive tariff builder

5) Update the dispatch rule to include transactions between the microgrid and the grid or other microgrids

5.7 Other MMC Capabilities

5.7.1 Network Topology Builder

1) GMC accommodates a group devoted to maintenance (modifications, upgrades, etc.) of the network and dealing mainly with the static data related to the network structure and elements.
2) Unlimited one-line diagram presentations in order to simulate multiple power systems analyses at the same time and visual the results side-by-side.
3) Handling and support of Single-phase system (2 and 3 wires) as well as panel systems
4) Be able to model and analyze unlimited sources and loads connected in looped or radial configuration.
5) Three-dimensional (3-D) database to track unlimited status configurations/scenarios (switching devices, motors, loads, etc.) as well as multiple engineering properties (as built and future expansion scenarios)
6) Multiple loading categories (conditions) with individual percent loading

5.7.2 Network Topology Management

GMC calculates the topology model based on real-time operating conditions such as meter readings, status of sources & loads as well as status of circuit breakers, switches, etc. The real-time network topology processor represents a base upon which state estimator and other electrical network analysis programs will operate.

5.7.3 Advanced Monitoring

1) GMC utilizes advanced functionality such as state estimation and the network topology to determine anticipated power system performance and behavior.
2) The aim of the state estimator and load distributor is to define a complete and consistent set of data of the entire power network (both, observable parts and unobservable parts).
3) A network solution is estimated, for the observable and unobservable portions of the network model, providing an accurate and reliable state of the power system.

4) Compare load flow vs estimated vs metered values
5) The state of the power system will be described by a collection of voltage vectors for a given network topology and parameters. The set of measurements used for state estimation The data that will be used for the state estimation are mainly:
    a. Status of circuit breakers and disconnect switches, , which are used to update the network model
    b. Measurements of branch flows, in MW, Mvar, or amperes
    c. Measurements of loads, in MW, Mvar, or amperes
    d. Measurements of bus section voltage magnitude
6) Thus, the input data for the state estiamtion consist of:
    a. Line and transformer flows (MW, MVAR, A)
    b. Loads (MW, MVAR, A)
    c. Generator unit outputs (MW, MVAR)
    d. Bus voltages (magnitudes)
    e. Measurement quality codes
    f. Measurement weighting factors
    g. Branch overload MVA or Amp limits
    h. Bus high/low voltage limits
    i. Series impedances and shunt admittances of all power equipment in the network model
7) Using these values, the state estimator examines the data for obvious data errors, determines those portions of the network which have sufficient telemetry to be observable, generates artificial measurements (called "pseudo" and "virtual" measurements) at locations where they are required for observability, and then computes the state of the power system providing the following output data:
    a. Estimated bus voltage magnitudes and phase angles
    b. Bus power injections (MW,MVAR)
    c. Currents (Amp)
    d. Estimated line and transformer flows
    e. Bad data indications
    f. Replacement values for bad data

   g. Historical bad data information
   h. Smoothed biases
   i. Smoothed standard deviations of measurement errors
   j. Information concerning estimated branch flows exceeding their limits
   k. Information concerning estimated bus voltages exceeding their limits

8) For the unobservable parts of the network, the state estimator delivers estimated values providing a network solution for the unobservable and non-telemetered portions of the network model. Unobservable network areas can be created whenever measurements are out-of-service or communication links fail.
9) Any unobservable areas is solved using the full network model. It is not permissible to create a reduced, equivalent representation for any portions of the fully-modeled network. In estimating a solution, the system utilizes and producse results which are consistent with all available information, including any available real time data, any recently telemetered data, and historical data or pseudo-measurements (complete model estimator).
10) As stated, a complete model estimator is used for the modelling of the parts of the internal power system, which are non-observable. This complete model estimator combines estimated and non estimated parts to one unique consistent network model. The aim is to define a loading condition which is as realistic as possible.
11) The complete model estimator will use, in addition to the parameters and inputs of the power system elements previously stated, the following input data:
   a. ‘Basic’ position of the switches outside the estimated area
   b. Estimated loading condition inside the estimated areas and at the boundary nodes
   c. Available measurements in the non-observable parts of the power system
   d. Pseudo-measurements and manual input data from the operator
   e. Measurement weights
   f. Series impedances and shunt admittances of all power equipment
   g. Overload branch flow limits and bus high/low voltage limits

5.7.4 Sequence of Events Playback

The GMC is capable of being configured to provide a complete picture of the electrical system from the stored data. This includes playback of a previously recorded monitored data, calculated system parameters, sequence of events, and message log.

6 Summary

The specifications for a Generic Microgrid Controller have been described and the description of the parameters used to define the MMC, BC, GC, LC and SC have been provided. The testing of the GMC specifications will be conducted in an OPAL-RT simulation of the UCI Microgrid in cooperation with Southern California Edison, using a purpose built controller by ETAP that conforms to the GMC specifications. Through the testing and on-going interaction with the IEEE 2030.7 Committee, the specifications will be fine-tuned and translated into an appropriate software language.