Microgrids Management

Controls and Operation Aspects of Microgrids

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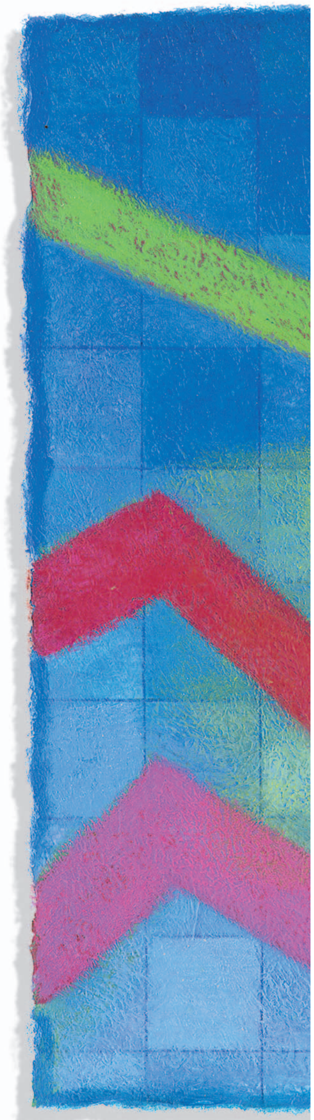

THE ENVIRONMENTAL AND ECONOMICAL BENEFITS OF THE MICROGRID, AND consequently its acceptability and degree of proliferation in the utility power industry, are primarily determined by the envisioned controller capabilities and the operational features. Depending on the type and depth of penetration of distributed energy resource (DER) units, load characteristics and power quality constraints, and market participation strategies, the required control and operational strategies of a microgrid can be significantly, and even conceptually, different than those of the conventional power systems. The main reasons are as follows:

- ✔ steady-state and dynamic characteristics of DER units, particularly electronically coupled units, are different than those of the conventional large turbine-generator units
- ✔ a microgrid is inherently subject to a significant degree of imbalance due to the presence of single-phase loads and/or DER units
- ✔ a noticeable portion of supply within a microgrid can be from "noncontrollable" sources; e.g., wind-based units
- ✔ short- and long-term energy storage units can play a major role in control and operation of a microgrid
- ✔ economics often dictate that a microgrid must readily accommodate connection and disconnection of DER units and loads while maintaining its operation
- ✔ a microgrid may be required to provide prespecified power quality levels or preferential services to some loads
- ✔ in addition to electrical energy, a microgrid is often responsible for generating and supplying heat to all or parts of its loads.

Digital Object Identifier 10.1109/MPE.2008.918702

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This article provides an overview of the existing microgrid controls, highlights the importance of power and energy management strategies, and describes potential approaches for market participation.

Microgrid Structure and Characteristics

Figure 1 shows a microgrid schematic diagram. The microgrid encompasses a portion of an electric power distribution system that is located downstream of the distribution substation, and it includes a variety of DER units and different types of end users of electricity and/or heat. DER units include both distributed generation (DG) and distributed storage (DS) units with different capacities and characteristics. The electrical connection point of the microgrid to the utility system, at the low-voltage bus of the substation transformer, constitutes the microgrid point of common coupling (PCC). The microgrid serves a variety of customers, e.g., residential buildings, commercial entities, and industrial parks.

The microgrid of Figure 1 normally operates in a grid-connected mode through the substation transformer. However, it is also expected to provide sufficient generation capacity, controls, and operational strategies to supply at least a portion of the load after being disconnected from the distribution system at the PCC and remain operational as an autonomous (islanded) entity. The existing power utility practice often does not permit accidental islanding and automatic resynchronization of a microgrid, primarily due to the human and equipment safety concerns. However, the high amount of penetration of DER units potentially necessitates provisions for both islanded and grid-connected modes of operations and smooth transition between the two (i.e., islanding and synchronization transients) to enable the best utilization of the microgrid resources.

DER units, in terms of their interface with a microgrid, are divided into two groups. The first group includes conventional or rotary units that are interfaced to the microgrid through rotating machines. The second group consists of electronically coupled units that utilize power electronic converters to provide the coupling media with the host system. The control concepts, strategies, and characteristics of power electronic converters, as the interface media for most types of DG and DS units, are significantly different than those of the conventional rotating machines. Therefore, the control strategies and dynamic behavior of a microgrid, particularly in an autonomous mode of operation, can be noticeably different than that of a conventional power system.

Furthermore, in contrast to the well-established operational strategies and controls of an interconnected power system, the types of controls and power/energy management strategies envisioned for a microgrid are mainly determined based on the adopted DER technologies, load requirements, and the expected operational scenarios. Figure 2 shows a schematic representation of the building blocks of a microgrid that includes load, generation/storage, electricity, and thermal grids. Figure 2 implies two levels of controls; i.e., component-level and system-level controls.

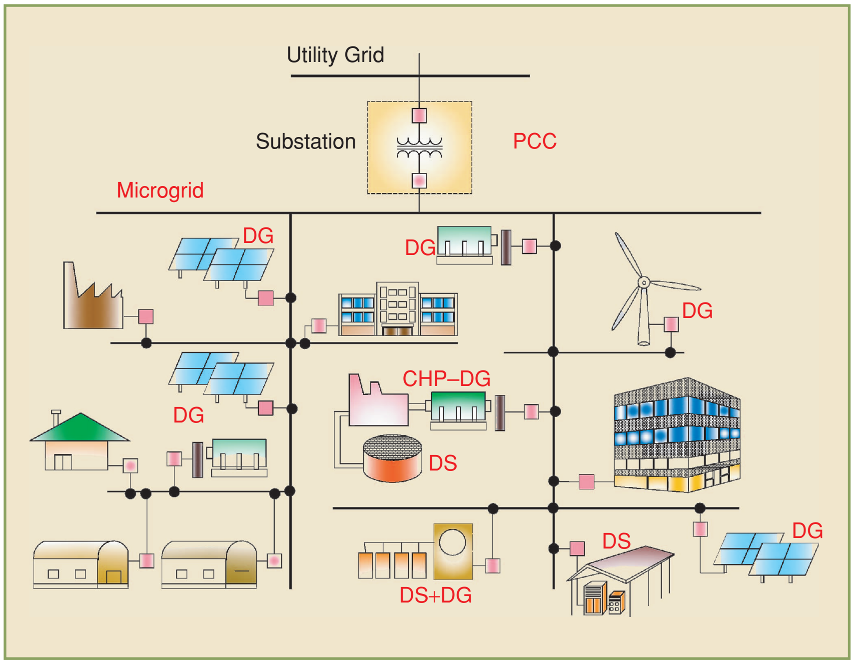

figure 1. A typical microgrid structure including loads and DER units serviced by a distribution system.

DER Units

Both DG and DS units are usually connected at either medium- or low-voltage levels to the host microgrid. Figure 3 shows a DG unit comprising a primary energy source, an interface medium, and switchgear at the unit point of connection (PC). In a conventional DG unit (e.g., a synchronous generator driven by a reciprocating engine or an induction generator driven by a fixed-speed wind turbine) the rotating machine:

- ✔ converts the power from the primary energy source to the electrical power
- ✔ also acts as the interface medium between the source and the microgrid.

For an electronically coupled DG unit, the coupling converter:

- ✔ can provide another layer of conversion and/or control; e.g., voltage and/or frequency control
- ✔ acts as the interface medium with the microgrid.

The input power to the interface converter from the source side can be ac at fixed or variable frequency or dc. The microgrid-side of the converter is at the frequency of either 50 or 60 Hz. Figure 3 also provides a high-level representation of a DS unit for which the "primary energy source" should be replaced by the "storage medium."

Table 1 outlines typical interface configurations and methods for power flow control of DG and DS units for the widely used primary energy sources and storage media, respectively. It should be noted that in addition to the two basic types of DG and DS units, a DER unit can be of a hybrid type; i.e., a unit that includes both "primary energy source" and "storage medium." A hybrid DER unit is often interfaced to the host microgrid through a converter system that includes bidirectional ac-dc and dc-dc converters.

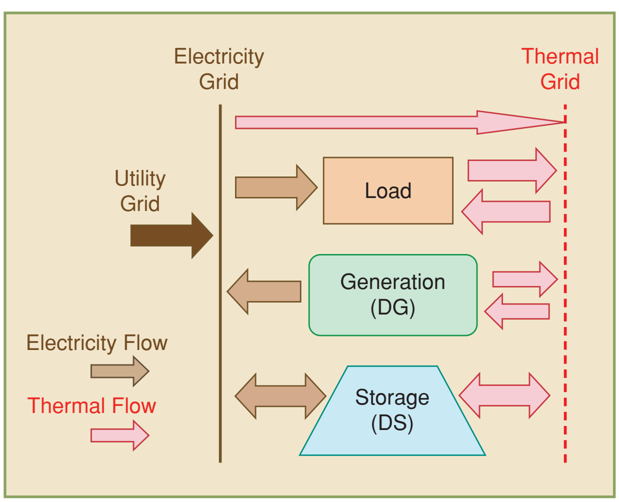

figure 2. A general representation of the microgrid building blocks.

In terms of power flow control, a DG unit is either a dispatchable or a nondispatchable unit. The output power of a

> The required control and operational strategies of a microgrid can be significantly, and even conceptually, different than those of conventional power systems.

dispatchable DG unit can be controlled externally, through set points provided by a supervisory control system. A dispatchable DG unit is either a fast-acting or a slow-response unit. An example of a conventional dispatchable DG unit is the configuration shown in Figure 4, which utilizes a reciprocating engine as its primary energy source. A reciprocating-engine-based DG unit is normally equipped with a governor for speed control and fuel in-flow adjustment. The automatic voltage regulator (AVR) controls the internal voltage of the synchronous generator. The governor and the AVR control real and reactive power outputs of the DG unit based on a dispatch strategy.

In contrast, the output power of a nondispatchable DG unit is normally controlled based on the optimal operating condition of its primary energy source. For example, a nondispatchable wind unit is normally operated based on the maximum power tracking concept to extract the maximum possible power from the wind regime. Thus, the output power of the unit varies according to the wind conditions. The DG units that use renewable energy sources are often nondispatchable units. To maximize output power of a renewable-energy-based DG unit, normally a control strategy based upon maximum point of power tracking (MPPT) is used to deliver the maximum power under all viable conditions.

Figure 5 shows three common architectures for an electronically interfaced DER unit. Figure 5(a) shows a nondispatchable photovoltaic (PV)-based DG unit for which the PV array, through a converter system, is interfaced to the host microgrid. The converter is a dc-dc-ac system composed of one dc-dc converter and one dc-ac converter. The configuration of Figure 5(a) can also represent a DG unit for which the primary energy source, in contrast to the PV array, is of a dispatchable nature; e.g., a fuel cell. Similarly, if the PV array of Figure 5(a) is substituted with a battery storage, it constitutes an electronically coupled DS unit.

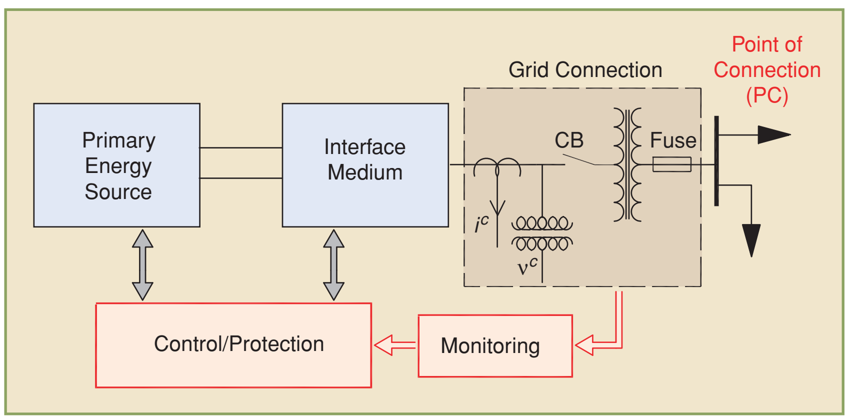

figure 3. Block representation of a DG unit.

table 1. Interface media for DER units.

	Primary Energy Source (PES)	Interface/Inversion	Power Flow Control
Conventional DG	Reciprocating engines small hydro	Synchronous generator	AVR and Governor control (+P, ±Q)
	Fixed-speed wind turbine	Induction generator	Stall or pitch control of turbine (+P, −Q)
Nonconventional DG	Variable-speed wind turbine Microturbine	Power electronic converter (ac-dc-ac conversion)	Turbine speed and dc Link voltage controls (+P, ±Q)
	Solar PV Fuel cell	Power electronic converter (dc-dc-ac conversion)	MPPT and dc link Voltage controls (+P, ±Q)
Long-Term Storage (DS)	Battery storage	Power electronic converter (dc-dc-ac conversion)	State-of-charge and/or output Voltage/frequency controls (±P/±Q)
Short-Term Storage (DS)	Super capacitor	Power electronic converter (dc-dc-ac conversion)	State-of-charge (±P, ±Q)
	Flywheel	Power electronic converter (ac-dc-ac conversion)	Speed control (±P, ±Q)

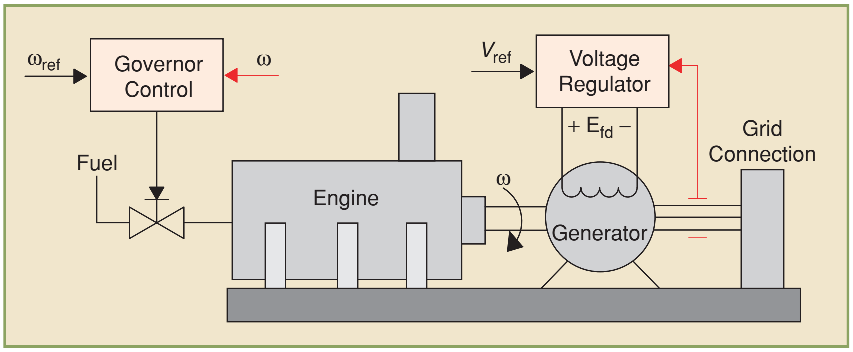

figure 4. Reciprocating engine generator as a dispatchable DG unit.

interface converter. Another feature is the capability of the interface converter to limit the short-circuit contribution of the unit to less than 200% of the rated current and practically prevent fault current contribution. In contrast to a conventional DG unit, an electronically coupled DG unit does not exhibit any inertia during the microgrid transients and thus has no intrinsic tendency to maintain the microgrid frequency. However, the converter fast controls can also be exploited to assist in frequency regulation. Another characteristic of the interface converter system of Figure 5 is that it provides some degree of electrical decoupling between the primary energy source and the distribution system, and thus the dynamic interactions between the two subsystems are often less severe compared with the case of a conventional DG unit.

Figure 5(b) shows a hybrid electronically coupled DER unit for which the converter system is composed of two parallel dc-dc converters and one dc-ac converter. Although the PV array provides nondispatchable power, the converter system can be controlled to provide a dispatchable power at the output of the unit. Figure 5(b) also implies that a nondispatchable wind-based DG unit can be converted into a dispatchable hybrid DER unit.

Figure 5(c) shows an electronically coupled genset DG unit that is augmented with a capacitive energy storage unit. The genset is a slow-acting dispatchable DG unit that is coupled to the host microgrid through an ac-dc-ac converter system. The capacitive storage unit is interfaced to the dc link of the ac-dc-ac converter system through a dc-dc converter and provides short-time power flow requirements during start up and/or acceleration/deceleration intervals of the slow genset.

A salient feature of an electronically coupled DER unit is its inherent capability for fast dynamic response through its

Microgrid Loads

A microgrid can serve electrical and/or thermal loads. In a grid-connected mode, the utility distribution system often can be considered as an electric "slack bus" and supply/absorb any power discrepancy in the microgrid-generated power to maintain the net power balance. Load or generation shedding within a microgrid is also an option if the net import/export power has hard limits based on operational strategies or contractual obligations.

In an autonomous mode of operation, load/generation shedding is often required to maintain the power balance and

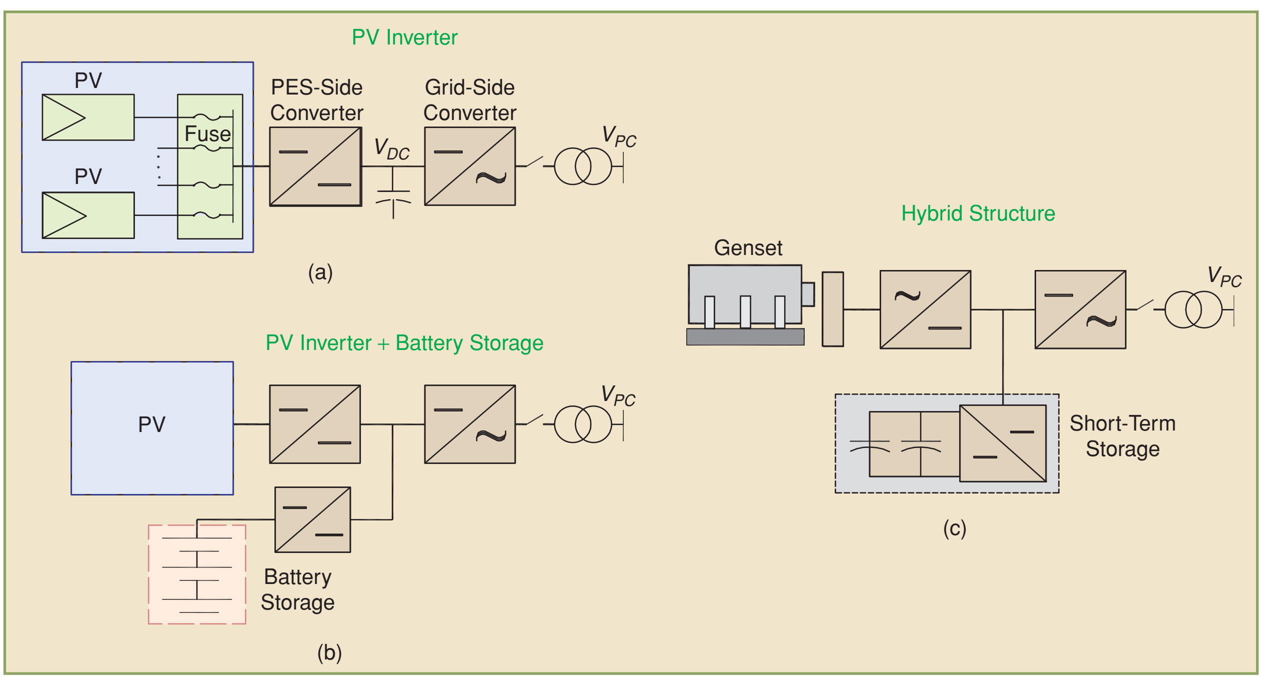

figure 5. Common structures for an electronically coupled DER unit: (a) nondispatchable DG, (b) and (c) disptachable DG plus DS.

consequently stabilize the microgrid voltage/angle. Therefore, the operating strategy must ensure that the critical loads of the microgrid receive service priority. Furthermore, operation of a microgrid should accommodate functions such as customer service differentiation, power quality enhancement of specific loads, and reliability improvement of prespecified load categories. Load control can also be exercised to optimize the ratings of DS units and dispatchable DG units by reducing the peak load and wide range of load variations.

In practice, part of a nonsensitive load can be considered a controllable load and entered into a demand response control strategy to either reduce the peak load and smooth out the load profile, or to schedule the load serving for specific time intervals when additional power, for instance, from intermittent DG units, is available. The noncontrollable part of a nonsensitive load is the first candidate for load shedding. Load shedding and demand response are normally executed and supervised through the energy management controller of the microgrid.

A noninteractive, grid-forming control is an explicit method for voltage and frequency control of a dispatchable unit, in the absence of the utility grid. Based on this strategy, a DER unit attempts to supply the balance of power while regulating the voltage and stabilizing the frequency of the autonomous microgrid. If two or more DG units share the load demand and concurrently respond to variations in the microgrid load, then an interactive control strategy through changing voltage and frequency of the DER units can be applied.

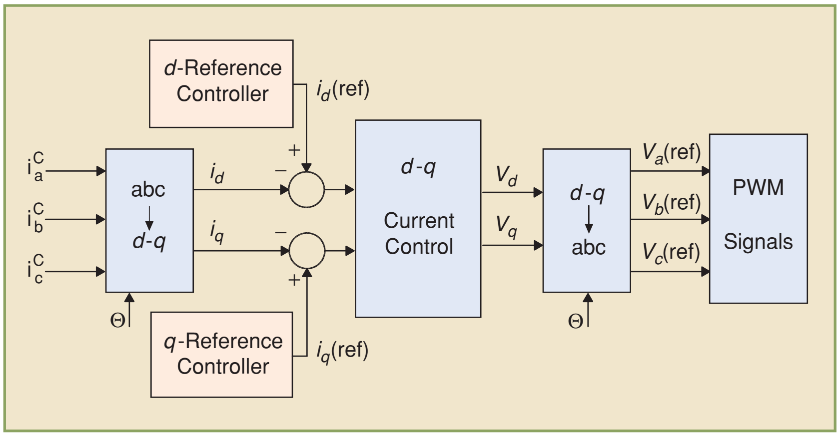

figure 6. "*dq*" current control of a VSC-interfaced DER.

DER Controls

Control strategies for DER units within a microgrid are selected based on the required functions and possible operational scenarios. Controls of a DER unit are also determined by the nature of its interactions with the system and other DER units. The main control functions for a DER unit are voltage and frequency control and/or active/reactive power control. Table 2 provides a general categorization of the major control functions of a DER unit and divides the strategies into the grid-following and grid-forming controls.

Each category is further divided into noninteractive and grid-interactive strategies. The grid-following approach is employed when direct control of voltage and/or frequency at the PC is not required. Furthermore, if the unit output power is controlled independent of the other units or loads (nondispatchable DER unit), it constitutes a grid-noninteractive strategy. An example of the grid-noninteractive strategy is the MPPT control of a solar-PV unit. A grid-interactive control strategy is based on specifying real/reactive power set points as input commands. The power set points are either specified based on a power dispatch strategy or real/reactive power compensation of the load or the feeder.

Grid-Following: Power Export Control

The grid-following power export control strategy is often used to control the DER output power within the voltage and frequency limits as determined by the microgrid. If the coupling converter is a voltage-sourced converter (VSC), a current-controlled strategy can be used to determine the reference voltage waveforms for the pulse-width modulation (PWM) of the VSC. The reference signals are also synchronized to the microgrid frequency by tracking the PC voltage waveform. The control strategy can be implemented in a synchronous "*dq*0" frame that specifies the direct (*d*-axis) and quadrature (*q*-axis) components of the converter output currents corresponding to the real and reactive output power components, respectively. Figure 6 shows a block diagram representation of a "*dq*0" frame controller.

Figure 6 shows that the "*d*-axis" and "*q*-axis" current components of the VSC are extracted through an "abc" to "*dq*0" transformation, then compared with the corresponding reference signals that are specified by the external power or voltage control loops. The error signals are applied to a *dq* current control block to determine the *d*- and *q*-component of the reference voltage signals V_d and

table 2. Classification of control strategies for electronically coupled DER units.

	Grid-Following Controls	Grid-Forming Controls
Noninteractive Control Methods	Power export (with/without MPPT)	Voltage and frequency control
Interactive Control Methods	Power dispatch Real and reactive power support	Load sharing (droop control)

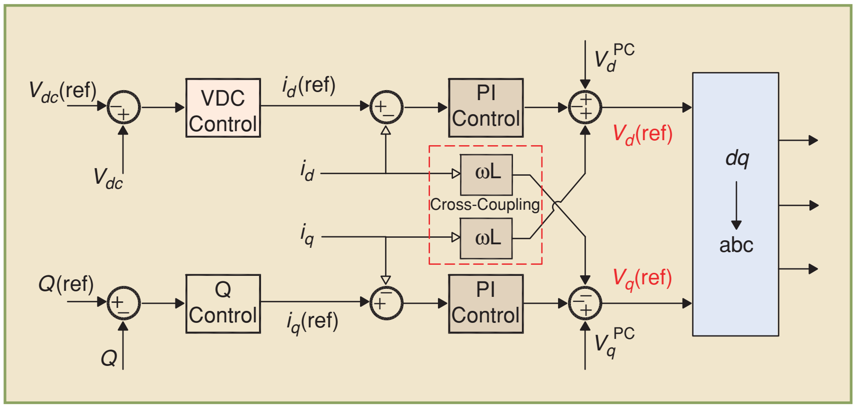

figure 7. Grid-following power export control diagram.

V_q. Finally, through a transformation from "*dq*0" to "abc," the three-phase reference signals for the PWM signal generator are determined. Details of the internal and external control blocks can vary based on the control modes and the type of primary source. Similar current control approaches can also be developed in the abc reference frame; e.g., for an unbalanced system.

Figure 7 shows a control block based on a power export strategy in which a dc-link voltage controller and a reactive-power controller replace the *dq* reference controllers of Figure 6, respectively. The input power extracted from the renewable energy source is fed into the dc link, which raises the dc-link voltage. The voltage controller counteracts the voltage rise by specifying an adequate value of the *d*-axis inverter current to balance the power in-flow and out-flow of the dc link.

The reactive power controller of Figure 7 specifies the reference value for the *q*-component of the converter current. The *Q*(ref) value is set to zero if the unity power factor is required. Figure 7 also shows further details of the *d-q* current control, including two proportional-integral (PI) controllers for the *d*- and *q*-axis current controls, the voltage feed-forward terms, and the cross-coupling elimination terms. The outputs from the current controllers, after transformation, constitute the reference voltages for the PWM signal generator. One of the main features of the current control strategy is its inherent capability to limit the converter output current during a microgrid fault and thus provide overcurrent protection for the converter and reduce the fault current contribution of the unit.

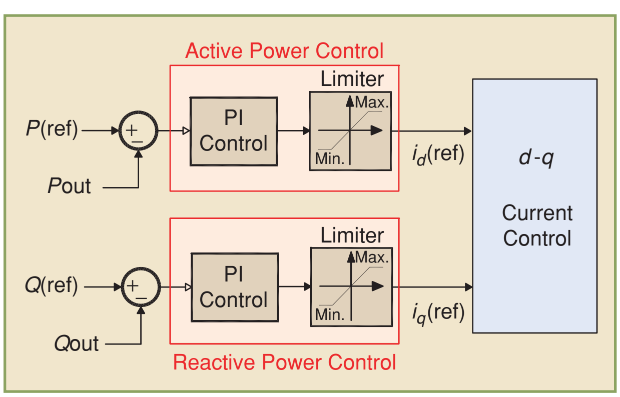

figure 8. Active and reactive power control.

Power Dispatch and Real/Reactive Power Support

Power dispatch and real/reactive power control strategies are normally used for output power control of dispatchable DER units, using prespecified reference values for real power dispatch and reactive power compensation. The control structure is conceptually similar to that of Figure 7. The main differences are in the methods used to generate the reference values. Figure 8 shows a control block diagram based on prespecified set points for real and reactive power controls of a DER unit. $P_{(\mathrm{ref})}$ and $Q_{(\mathrm{ref})}$ are the power set-points, and P_{out} and Q_{out} are the real and reactive power outputs calculated from the measured output voltages and currents of the unit.

The $P_{(\mathrm{ref})}$ and $Q_{(\mathrm{ref})}$ values can be set by a supervisory power management unit or locally calculated according to a prespecified power profile to optimize real/reactive power export from the unit. Other commonly applied methods are based on compensating variations in the local load, peak shaving profiles, and/or smoothing out fluctuations in the feeder power flow. Two specific cases of reactive power compensation are based on voltage regulation of the unit at the PC and power factor compensation.

Grid-Forming Controls

The grid-forming control strategy emulates behavior of a "swing source" in an autonomous microgrid. A grid-forming unit within a microgrid can be assigned to regulate the voltage at the PCC and dominantly set the system frequency. The unit should be adequately large and have adequate reserve capacity to supply the power balance. If two or more DER units actively participate in grid stabilization and voltage regulation, then frequency-droop and voltage-droop control strategies are used to share real and reactive power components. In this case, the voltage and frequency of the microgrid may deviate from the rated values, within acceptable limits, depending on the load level and the droop characteristics.

Figure 9 shows frequency-droop (*f-P*) and voltage-droop (*v-Q*) characteristics where each is specified by its slope (k_{fP} or k_{vQ}) and a base point representing either the rated frequency (f_o, P_o) or the nominal voltage (V_o, Q_o), respectively. The droop coefficients and the base-points can be controlled through a restoration process to dynamically adjust the operating points of the units. This is achieved by dynamically changing the power-sharing levels to set the frequency and voltages at new values. The restoration action is normally imposed very slowly and may also be exploited during resynchronization of an autonomous microgrid.

A block diagram of a droop control strategy is shown in Figure 10. The inputs to the controller are the locally measured deviations in the frequency and the terminal voltage of the unit. If DER units have different capacities, the slope of each droop characteristic is selected proportional to the rated capacity of the corresponding unit to prevent overloading.

Power and Energy Management

Sound operation of a microgrid with more than two DER units, especially in an autonomous mode, requires a power management strategy (PMS) and an energy management strategy (EMS). Fast response of the PMS/EMS is more critical for a microgrid compared with a conventional power system. The reasons are:

- ✔ presence of multiple, small DER units with significantly different power capacities and characteristics
- ✔ potentially no dominant source of energy generation during an autonomous mode; i.e., lack of infinite bus
- ✔ fast response of electronically coupled DER units that can adversely affect voltage/angle stability when appropriate provisions are not in place.

Figure 11 shows information/data flow and functions of a PMS/EMS for a microgrid. The real-time management block receives the present and the forecasted values of load, generation, and market information to impose appropriate controls on power flow, output generation, consumption level of the utility grid, dispatchable sources, and controllable loads, respectively.

The PMS/EMS assigns real and reactive power references for the DER units to:

- ✔ appropriately share real/reactive power among the DER units
- ✔ appropriately respond to the microgrid disturbances and transients
- ✔ determine the power set points of the DER units to balance the microgrid power and restore the frequency
- ✔ enable resynchronization of the microgrid with the main grid, if required.

In a grid-connected mode, the DER units supply prespecified power, e.g., to minimize power import from the grid (peak shaving), and each unit is controlled to represent either a (real/reactive power) PQ-bus or a real-power/voltage) PV-bus. Thus, the main grid is expected to accommodate the difference in real/reactive power supply and demand within the microgrid. However, in an autonomous mode, the output power of the units must meet the total load demand of the microgrid. Otherwise, the microgrid must undergo a load-shedding process to match generation and demand. In addition, fast and flexible real/reactive power control strategies are required to minimize the impact of microgrid dynamics,

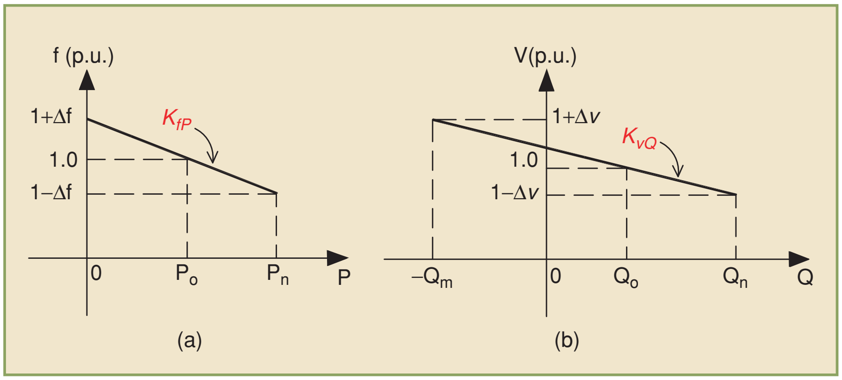

figure 9. Droop characteristics for load sharing among multiple DER units: (a) *f-P* droop, (b) *v-Q* droop.

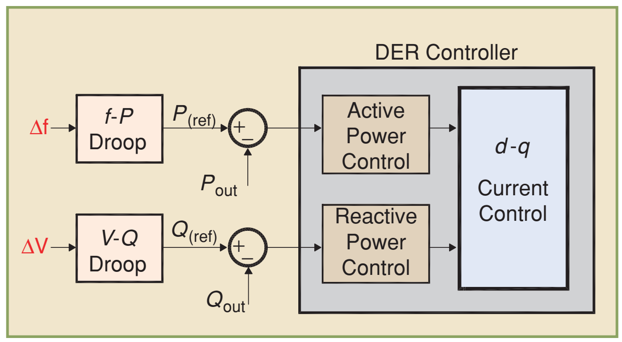

figure 10. Droop control strategy.

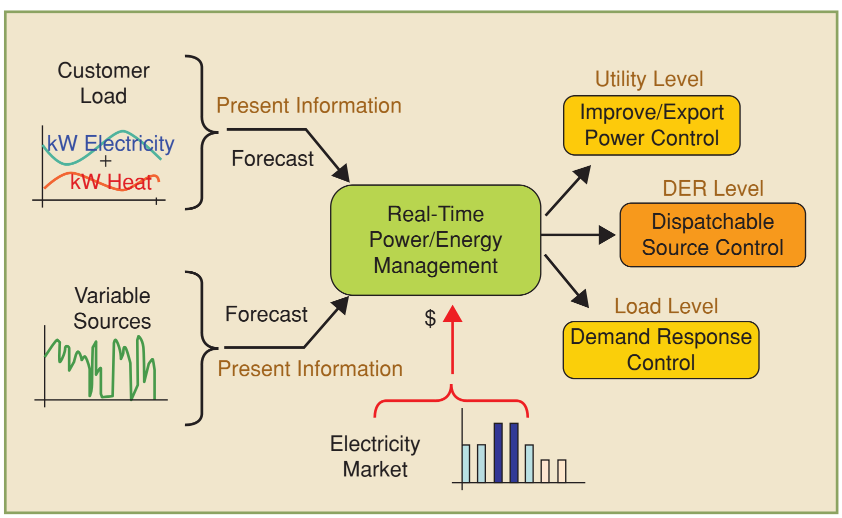

figure 11. Information flow and functions of a real-time PMS/EMS for a microgrid.

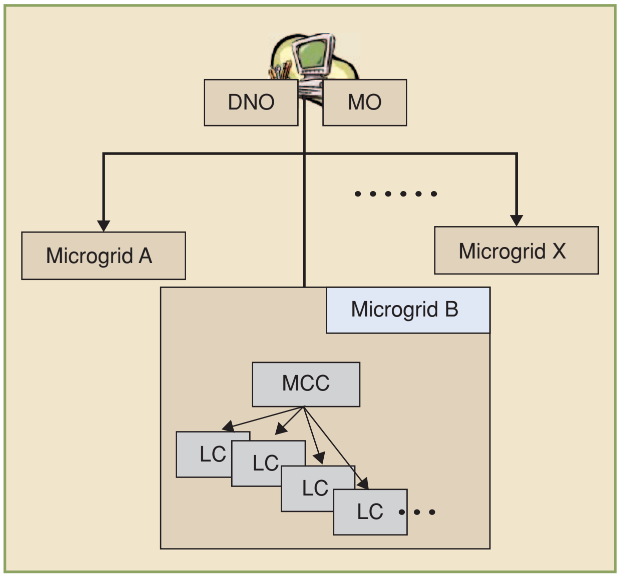

figure 12. A microgrid supervisory control architecture.

e.g., islanding transients, and damp out power and frequency oscillations. The PMS/EMS should accommodate both short-term power balancing and long-term energy management requirements.

The short-term power balancing may include:

- ✔ provisions for load-following capability, voltage regulation, and frequency control based on real power sharing among DER units and/or load shedding to alleviate power mismatch
- ✔ provisions for acceptable dynamic response, and voltage/frequency restoration during and subsequent to transients
- ✔ provisions to meet power quality constraints of sensitive loads
- ✔ provision for resynchronization subsequent to the main system restoration.

The long-term energy management may include:

- ✔ provisions to maintain an appropriate level of reserve capacity while rescheduling the operating points of dispatchable DER units based on an optimization process to a) control the net power import/export from/to the main grid, b) minimize power loss, c) maximize power outputs of the renewable-based units, and/or d) minimize the cost of energy production of fuel-based units.
- ✔ consideration for specific requirements/limitations of each DER unit, including type of unit, cost of generation, time dependency of the prime source, maintenance intervals, and environmental impacts
- ✔ provisions for demand response management (load-profile control) and restoration of nonsensitive loads that are disconnected/shed during the microgrid transients; for instance, in response to a load-shedding requirement subsequent to an islanding event.

Microgrid Supervisory Control

A microgrid, through its control system, must ensure all or a subset of functions (e.g., supply of electrical and/or thermal energy, participation in the energy market, prespecified service level for critical loads, black start subsequent to a failure, provision for ancillary services, etc). The objectives are achieved through either a centralized or a decentralized supervisory control that includes three hierarchical levels as shown in Figure 12:

- ✔ distribution network operator (DNO) and market operator (MO)
- ✔ microgrid central controller (MCC)
- ✔ local controllers (LCs) associated with each DER unit and/or load.

The DNO is intended for an area in which more than one microgrid exists. In addition, one (or more) MO is responsible for the market functions of each specific area. These two entities do not belong to the microgrid but are the delegates of the main grid. The main interface between the DNO/MO and the microgrid is the MCC. The MCC assumes different roles ranging from the maximization of the microgrid value to coordination of LCs.

The LC controls the DER units and the controllable loads within a microgrid. Depending on the control approach, each LC may have certain level of intelligence. In a centralized operation, each LC receives set points from the corresponding MCC. In a decentralized operation, each LC makes decisions locally. Of course, in any approach, some decisions are only locally made; e.g., an LC does not require a command from the MCC for voltage control. In a centralized approach, the LCs follow the command(s) of the MCC during a grid-connected mode of operation and have the autonomy to:

- ✔ perform local optimization for power exchange of the DER units
- ✔ switch to fast load tracking method(s) subsequent to transition to an autonomous mode.

Based on a DER bidding strategy and a high-level optimization process, the MCC provides set points to the DER

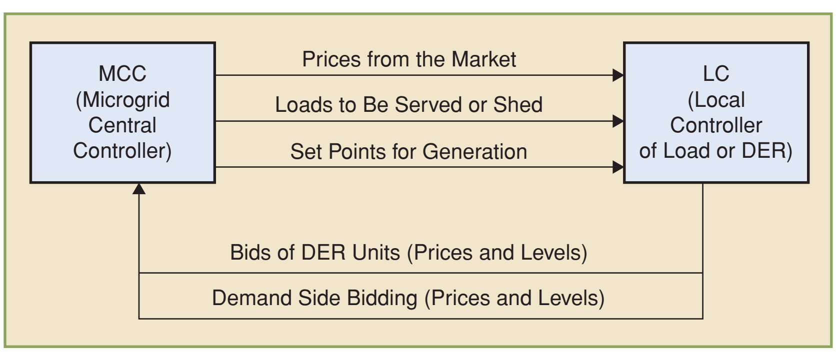

figure 13. Information flow in a centralized controlled microgrid.

Existing power utility practice often does not permit accidental islanding and automatic resynchronization of a microgrid, primarily due to the human and equipment safety concerns.

units and decides whether or not to serve or control low-priority loads. In a decentralized approach, the control decisions are made by the DER LCs (e.g., power optimization to meet the load demand, and maximizing power export to the main grid based on market prices). Furthermore, LCs must ensure safe and smooth operation of the loads they control.

Centralized Microgrid Control

Through a centralized control, the MCC optimizes the microgrid-exchanged power with the host system, thus maximizing the local production depending on the market prices and security constraints. This is achieved by issuing control set points to DER units and controllable loads within the microgrid. Figure 13 illustrates the information exchange path of a centralized control strategy and indicates that a two-way communication between the MCC and each LC is required. The communication can be through telephone lines, power line carriers, or a wireless medium. The MCC takes decisions for prespecified time intervals; e.g., every 15 minutes for the next hour or hours. Based on the market prices and unit capacities, the DER LCs issue bids to the MCC regarding their production levels. Similarly, the load LCs issue bids for their demands considering their priorities for service. Based on the market policy, the MCC takes into account:

- ✔ DER and loads bids
- ✔ market prices
- ✔ network security constraints
- ✔ demand and/or renewable production forecasts

and, using an optimization process, issues:

- ✔ production set points for DER units
- ✔ set points for the loads to be served or shed
- ✔ market prices for the next optimization period to enable LC bidding processes.

Based on the MCC-issued signals, the LCs adjust generation and demand levels and prepare bids for the subsequent period. The functions that can be implemented to perform centralized control of a microgrid include load/generation/heat forecasting and functions regarding unit commitment, economic dispatch, and security constraints. As an example, Figure 14 displays the daily economic scheduling of a 400-kW microgrid comprising one 100-kW microturbine unit, one 100-kW fuel-cell unit, one 40-kW wind-turbine unit, and two 10-kW PV units, assuming that the DER bids reflect fuel costs and investment payback and the 8 October 2003 market prices of the Amsterdam Power Exchange.

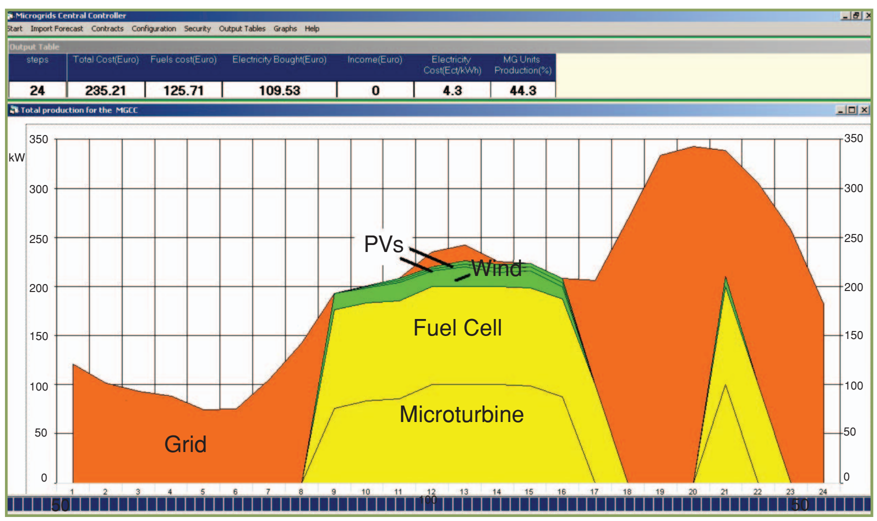

figure 14. Display of DER dispatch and energy imported from the grid.

Decentralized Microgrid Control

A decentralized control approach intends to provide the maximum autonomy for the DER units and loads within a microgrid. The autonomy of the LCs implies that they are intelligent and can communicate with each other to form a larger intelligent entity. In decentralized control, the main task of each controller is not necessarily to maximize the revenue of the corresponding unit but to improve the overall performance of the microgrid. Thus, the architecture must be able to include economic functions, environmental factors, and technical requirements; e.g., black start. These features indicate that a multi-agent system (MAS) can be a prime candidate to develop a decentralized microgrid control.

Conceptually, the MAS is an evolved form of the classical distributed control system with capabilities to control large and complex entities. A main feature of the MAS that distinguishes it from the classical distributed control techniques is that the software within each agent can imbed local intelligence. Each agent uses its intelligence to determine future actions and independently influences its environment. The artificial-intelligence-based methods (e.g., neural network or fuzzy systems) can be accommodated within the MAS.

An intelligent microgrid requires a fairly advanced communication system with capabilities similar to the human speech; e.g., the Agent Communication Language (ACL) that provides an environment for information and knowledge exchange. The need for a high-level communication environment can be shown by considering the communication needs of two agents within a microgrid. For example, at a given time one may have an instantaneous surplus of 1,500 W and the other may need 500 W. It is neither efficient nor required to provide the exact values, since the situation can change

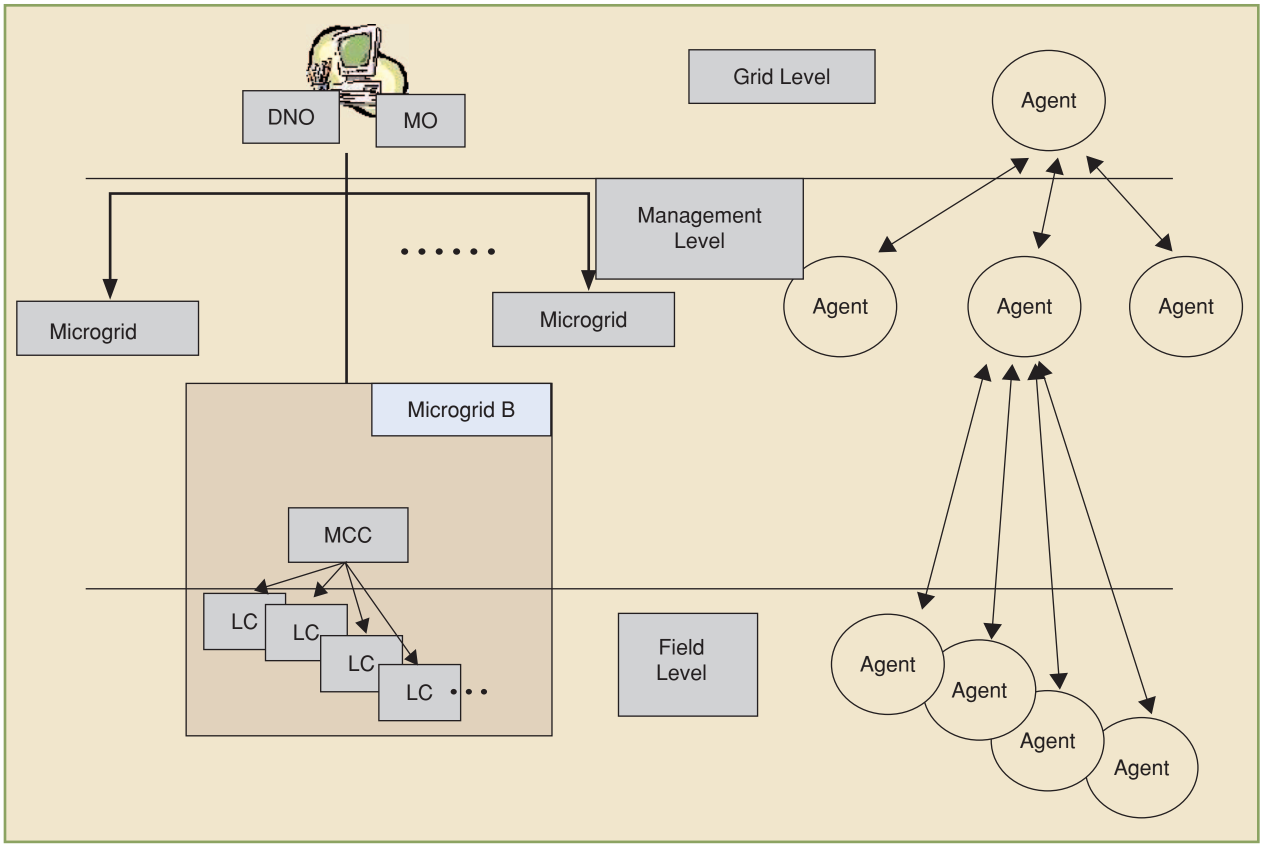

figure 15. Schematic diagram of the MAS architecture for a decentralized microgrid control.

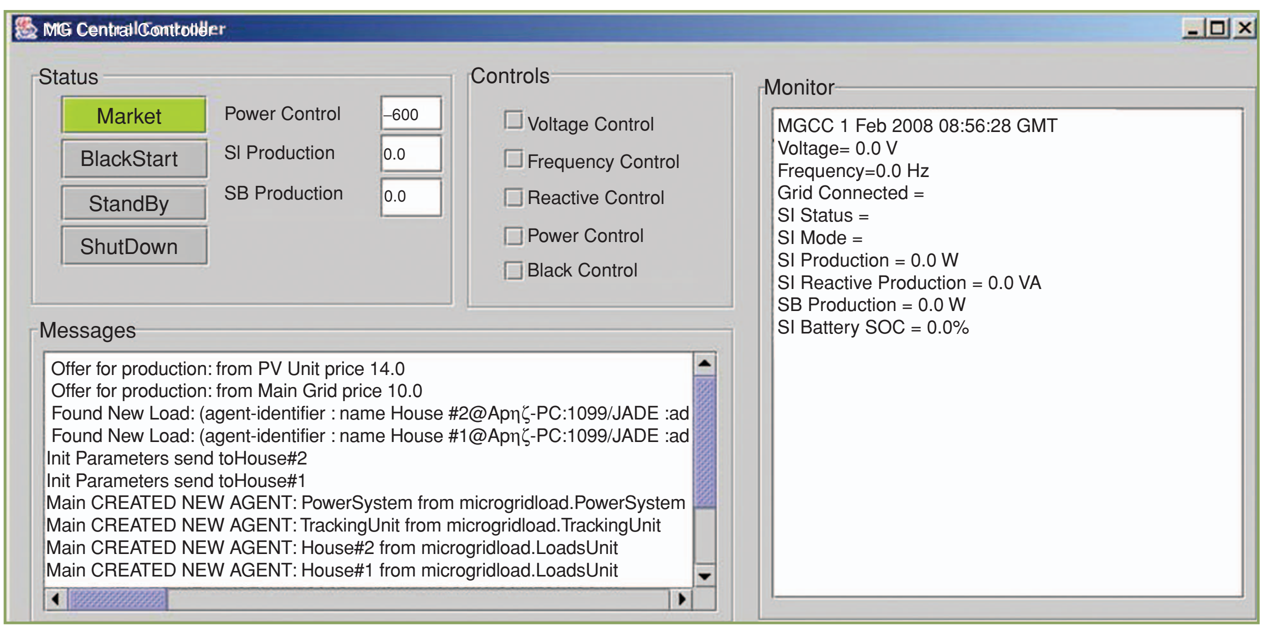

figure 16. The main frame of the MCC agent controlling a microgrid.

Sound operation of a microgrid with more than two distributed energy resource units, especially in an autonomous mode, requires a power management strategy and an energy management strategy.

within a short time. The ACL provides the environment to exchange messages of the form "I have currently some watts and do not expect to use them in the next 30 minutes" or "I need a few extra watts in the next 30 minutes."

The agents not only exchange simple values and on-off signals but also knowledge, commands, beliefs, and procedures to be followed through the ACL. For example, the agent that controls a load can participate in the local microgrid market by sending a request message to all DER agents stating the amount of required energy. Furthermore, the object-oriented nature of the ontology and data abstraction enables each agent to handle only the necessary or allowable information and knowledge.

Figure 15 shows a decentralized microgrid control structure. The higher level corresponds to a medium-voltage network and its agent is responsible for communication between the microgrid and the DNO and/or MO and the message exchange regarding the energy market. The medium level is the management level in which the agents coordinate:

- ✔ controllers of DER/load units
- ✔ market participation
- ✔ possible collaborations with the adjacent microgrids.

The market operation assumes that one agent is charged for negotiations with the MO; however, the bids and the offers result from negotiations among the local agents. The lower level, which is also called the field level, comprises the main elements of the MAS that correspond to the LCs. Operation of an LC requires an external part and an inner part. The external part provides interface with the microgrid, and it is common for all LCs to exchange set points, bids, and commands. The inner part is specific to each LC and responsible for translating orders and/or set points and applying them to the corresponding unit.

Figure 16 shows a screen of an MCC agent of a modular laboratory-scale microgrid, comprising a solar-PV unit, a battery bank, and a panel of controllable loads. The screen is used to monitor the main variables of the microgrid; e.g., the battery production, voltage and state of charge, and its market participation. Similar screens are available for the other agents.

The agent-based approach requires splitting a complex problem into its components and dealing with each separately. The agent organization constitutes a community where several tasks should be fulfilled depending on the levels where the agents operate; i.e., field level, management level, and grid level. The challenge is to develop the architecture such that a new functionality requires minimum changes in the existing agent-based software. To add a new functionality, all that should be required is to train the agents to deal with a new type of message or a new object in the ontology. In more advanced implementations, the agents could learn to solve a problem on their own.

Conclusions

Market acceptability of DER technologies and the gradual and consistent increase in their depth of penetration have generated significant interest in integration, controls, and optimal operation of DER units in the context of microgrids. Initially, microgrids were perceived as miniaturized versions of the conventional power systems, and intuitively their control/operational concepts were based on scaled-down and simplified versions of control/operational concepts of large power systems. This article highlighted the main differences between microgrids and large power systems and on that basis advocates for a fresh approach to the development of control and operational concepts for microgrids.

For Further Reading

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