# Intelligent Control System for Microgrids Using Multiagent System

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***Abstract*— This paper presents an intelligent control of a microgrid in both grid-connected and islanded modes using the multiagent system (MAS) technique. This intelligent control consists of three levels. The first level is based on local droop control, the second level compensates power balance between the supply and the demand optimally, and the third level is at the system level based on electricity market. An intelligent MAS was developed and implemented based on foundation for intelligent physical agents standards by representing each major autonomous component in the microgrid as an intelligent software agent. The agents interact with each other for making their own decisions locally and optimally. The coordination among the agents ensures power quality, voltage, and frequency of the microgrid by determining the set points that optimize the overall operation of the microgrid. The proposed control architecture and strategies for the real-time control of microgrids were analyzed in detail, and tested under various load conditions and different network configurations. The outcomes of the studies demonstrate the feasibility of the proposed control and strategies, as well as the capability of the MAS technique for the operation of microgrids.**

***Index Terms*— Grid-connected operation, information and communications technology-enabled architecture, intelligent control, islanded operation microgrid, multiagent system (MAS).**

## I. Introduction

MICROGRIDS are low-voltage power distribution systems with distributed energy resources, such as photovoltaic (PV) systems, fuel cells (FCs), and microturbines together with storage devices, such as flywheels, energy capacitors and batteries, and controllable loads, offering good control capabilities over the network operation. Microgrids can be interconnected to the main power grid or islanded from the main power grid [1], [2] based on the operating conditions and the status of the microgrid and the main power grid. The control and management of microgrids concerns the functions such as energy management, system stability, voltage quality, active and reactive power flow control, islanding detection, grid synchronization, and system recovery. Nowadays, microgrid control and energy management are gaining significance in research due to its distributed characteristics and necessity of advance control capabilities for the modern active network operation [3].

In recent years, interest in the multiagent system (MAS) technique [4] has been growing in order to deal with the complex and distributed problems in electrical power engineering. MAS technology is being investigated in a variety of applications in power engineering, including system restoration [5], [6], disturbance diagnosis [7], [8], and secondary voltage control [9]. Very recently, agent-based technology has been deployed to manage power distribution systems [10]–[14]. McArthur *et al.* [15], [16] gave an insight into concepts, approaches, technical problems, and potential values of the MAS for power engineering applications. In addition, standards, tools, supporting technologies, and design methodologies that could be incorporated for the implementation of MAS for power engineering were described. In-depth theory of autonomous systems in power system control and operation is discussed in [17]. Dimeas and Hatziargyriou [18]–[20] have described the agent-based technology for the control of microgrids and presented how local intelligence of agents can provide optimal and effective control solutions. Their research mainly focused on the implementation of real-time market-based microgrid operation. In addition, the applications of MAS in power engineering are highlighted in [21] and [26]. These research works show the potential of this distributed computational intelligent technique for the future power system operation.

In this paper, an intelligent MAS architecture for the control and management of a microgrid is proposed. Logenthiran *et al.* [27] have presented an MAS for a real-time operation of a microgrid through a real-time digital simulator, but it mainly concentrates only on the real-time power management. This paper deals with a real-time control of microgrid from a power electronics perspective, and the implementation issues are discussed in detail. Intelligent control concepts used to ensure stable real-time operation are also presented. In the test system, generators and FCs are capable of producing controlled active power on demand. Hence, they are used to regulate voltage and frequency during islanded operation. In contrast, PV system is not a dispatchable source because its output power mainly depends on climatic conditions. Therefore, it is optimally used as a supplementary source during the operational mode of the microgrid. Furthermore, a power-sharing method was developed for dispatching distributed generators (DGs) in the microgrid.

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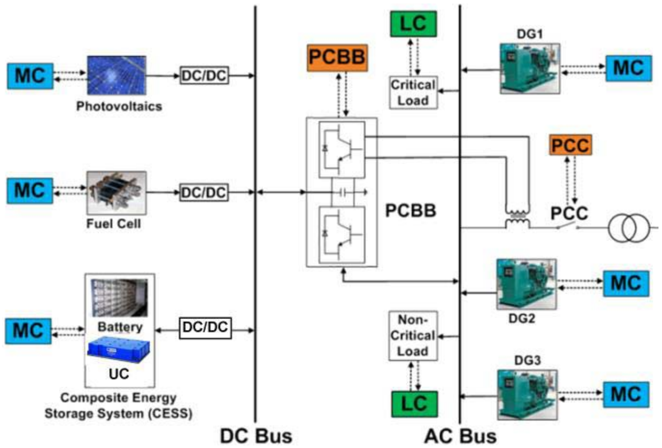


Fig. 1. Configuration of a hybrid microgrid.

To effectively control distributed resources within a microgrid, distributed and cooperative control architecture is facilitated within the MAS technology. Control strategies were developed by representing each major component in the microgrid as an autonomous intelligent agent, which is able to communicate with other agents to make its own decisions. The MAS was implemented in Java Agent DEvelopment Framework (JADE) [28], which is an open source foundation for intelligent physical agent (FIPA) [29] complaint multiagent platform. The microgrid was modeled in MATLAB. A real-time communication interface between the MAS and the microgrid was implemented.

The remaining paper is structured as follows. Section II explains a microgrid configuration and its main components. Section III proposes an ICT-enabled control architecture. Section IV presents the implementation of the MAS. Section V describes the implementation of distributed control strategies. Section VI demonstrates the effectiveness of the proposed control for operation of a hybrid microgrid. Finally, the conclusions are given in Section VII.

## II. Configuration of a Microgrid

This paper considers a hybrid microgrid that is suitable for integrating renewable and distributed energy resources as well as including an energy storage system. Fig. 1 shows a schematic configuration of a hybrid microgrid, which was modeled in MATLAB. Microgrid has several distributed energy resources and each resource has their own characteristics. They are controlled by separate microsource controllers (MCs)/agents. If there are different types of energy resources with different characteristics and most of them need some level of independence decision making, then multiagent modeling of the resources is most suitable approach. Having multiple interacting agents could speed up a system's operation by providing a method for parallel computation based on the demand. If control and responsibilities are sufficiently shared among different agents, the system can tolerate failures by one or more of the agents. It is easier to add agents in an MAS. Hence, parallelism, robustness, and scalability are the key benefits of MASs.

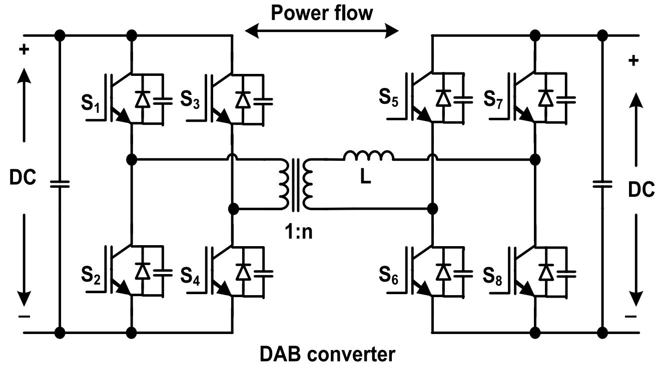


Fig. 2. DAB bidirectional dc–dc converter.

### A. Microsources

The microgrid consists of several distributed energy resources, such as PV system, FC, and DGs. They are connected via suitable power electronic interfaces. PV system generates power from solar radiation that varies with time. FC operates under steady-state conditions. The available models of PV and FC [30] were used in the microgrid modeling. All these distributed energy resources have their own MCs. In order to construct the test case, real insolation and temperature data for PV were used. DGs participate in an electricity market that is run by the secondary level control. In the case study, three DGs operating with diesel, biodiesel, and natural gas were included. Their power outputs are controlled based on their fuel costs.

### B. Composite Energy Storage System

Energy storage is extremely important in a renewable powered microgrid due to the intermittent nature of renewable energy sources and continuous variations in load-side demand [31]. Composite energy storage system (CESS) consists of a high energy density storage component such as battery to meet the demands of intermittent nature of renewable energy sources such as PV systems and high-power density storage element like ultracapacitor to meet quick fluctuations of load demands. In this paper, a battery bank and an ultracapacitor-based CESS is utilized to smooth out power fluctuations in the renewable energy generation, thereby improving the reliability and efficiency of microgrids. The dc bus voltage of microgrid is fixed and controlled by CESS. A real-time CESS model was used to model the microgrid.

The power interface of CESS is achieved through the dual-active-bridge (DAB) converter as shown in Fig. 2 and its simplified equivalent circuit is shown in Fig. 3. Any number of parallel DAB branches can be used to meet the requirements of CESS. Power transfer is achieved by phase shifting the voltage across the primary and secondary sides of the high-frequency transformer. The detailed operating principle of DAB and its model is presented in [32] and [33].

The average output current of the DAB converter is given by

$$I_o = \frac{T_S n V_{\text{in}}}{2L}(d - d^2) \tag{1}$$

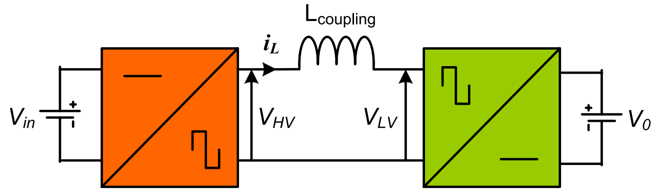


Fig. 3. Simplified equivalent circuit of DAB dc–dc.

where $I_0$ is the output current on the secondary side, $d$ is controlled phase shift, $V_{\text{in}}$ is the input voltage on the primary side, $L$ is the coupling inductance, $T_s$ is switching time, and $n$ is the turns ratio of transformer.

The average output power of the DAB converter is expressed as

$$P_0 = \frac{nV_{\text{in}}V_0T_S}{2L}(d - d^2) \tag{2}$$

$$P_0 = V_0I_0 \tag{3}$$

$$P_0 = \eta P_{in} \tag{4}$$

where $P_{\text{in}}$ is input power on the primary side, $P_0$ is output power on the secondary side, $\eta$ is conversion efficiency, and $V_0$ is secondary side terminal voltage.

Lumped model of energy storages in CESS is characterized by energy capacity, power ratings, and maximum ramp rate of power. The state-of-charge (SOC) of CESS is calculated based on current integration, which is

$$\Delta\text{SOC} = \frac{\Delta Q}{Q} = \frac{\int i_{\text{ES}}dt}{Q} \tag{5}$$

where $Q$ is rated capacity and $i_{\text{ES}}$ is current drawn from energy storage.

### C. Power Electronic Interfaces

Power electronic interfaces are essential to connect any type of distributed energy resource to the microgrid. With the development of solid-state-based packages and advances in circuit topologies, power electronic devices can convert any form of electrical energy to a more desirable and usable form. An important advantage of power electronics is its extremely fast response time. Power electronic interfaces can respond to power quality issues within a subcycle range. To maximize output power of PV, the PV system is connected through a maximum powerpoint tracking (MPPT) system that has a dc/dc converter with a simple control scheme for all conditions. Because of the low output voltage of FC, dc/dc converter of FC steps up the voltage to the dc bus voltage of 800 V. A bidirectional dc–dc converter is required to interface the CESS to the dc bus for controlling the dc bus voltage and the power flow. DAB converter is a promising configuration for bidirectional power transfer and this can be achieved by phase shifting primary and secondary side bridge voltages. The isolation between the energy storage and the load is fulfilled by a high frequency transformer [32], [33]. High-frequency transformer specifications are output power is 70 kVA, input voltage is 220 V with an output voltage of 800 V, and operating frequency of 20 kHz. An interleaved current-fed full-bridge converter and a DAB converter are selected for FC and CESS. A power converter building block (PCBB) is kept in the system to facilitate the functions of dc/ac bus inverter, active filter, and grid-connected inverter. The power converters were modeled by switching average models described in [34] and [35].

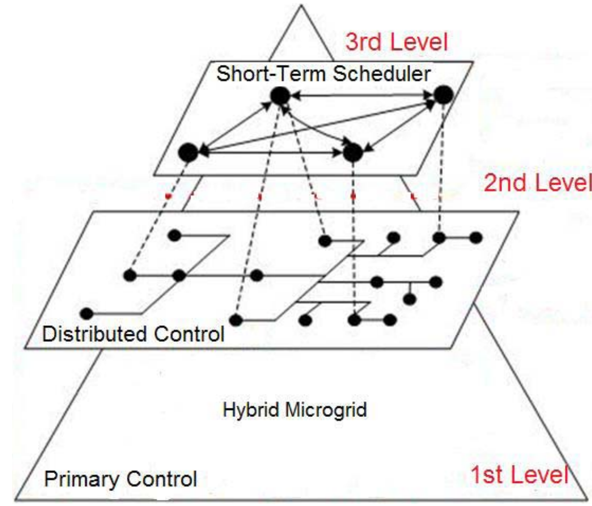


Fig. 4. Three-level control architecture for microgrids.

## III. Proposed Control Architecture

Smart grid, a future power system, looks for fully decentralized control architecture but it cannot be changed suddenly from centralized to decentralized control architecture. It should be changed gradually. Currently, researchers propose some new partially decentralized control architectures for different types of power systems and do case studies to validate them.

Various control and management architectures have been proposed in the literature for microgrid control. In this paper, the three-level control architecture, as shown in Fig. 4, is proposed for microgrid control. The proposed control concepts are defined according to the performance and requirements of the overall system. Even though this paper mainly focuses on the real-time control of microgrid, it presents all control levels from the bottom level to the top level.

### A. First-Level Control

The bottom-level control incorporates local controllers (LCs) for microgrid elements. They have the ability to respond quickly. The LCs control the resources without any communications. Controllers respond based on local measurements and system dynamics to ensure power balance between supply and load. These controllers provide instantaneous power balance when frequency deviation occurs. The first-level control is designed using a governor control system, which controls the change in frequency or speed of generators when any incident occurs. The governor control system adjusts the outputs of generators that are required to participate in this control by setting the droop values according to specifications. A droop loop is included as a part of the speed governor, so that the system load is shared among multiple generators. The system requires the next level of control (i.e., the second-level control) to compensate any power mismatch. The time frame of this primary response is in seconds.

### *B. Second-Level Control*

The second-level control is used for compensating power imbalance between the power supply and the load optimally. The second-level control is also responsible for control actions when a microgrid frequency deviation occurs. It calculates the amount of power needed to bring the system to the reference frequency, and shares that power among the resources optimally. This control strategy is based on real-time measurements, and the control procedure takes all the sources into account. The new generation set points are produced by adding the calculated power correction to the initially assigned power. In this paper, these are carried out by the corresponding individual agents. The power settings of microsources are specified initially according to the schedule from the third-level control. The second-level control also does synchronizing function of the microgrid and the main grid for facilitating the transition between islanded mode and grid-connected mode. This control operates slower than the first-level control. It provides a response at time intervals of 5 min.

### *C. Third-Level Control*

The third-level control is at the top of the control architecture, and implemented with a short-term scheduler (i.e., day-ahead planner) whose basic functionalities include generation scheduling, demand side management, market participation, load forecasting, wholesale energy price forecasting, and renewable energy forecasting [36]. This control performs supply–demand matching in 30-min intervals as wholesale market price varies in 30-min intervals. The corresponding agents in the MAS for the third-level control have different types of generation scheduling algorithms and strategies based on the rules and policies applied in the microgrid. In order to carry out the operation of the microgrid, the second level and the third level of the control systems coordinate with each other. This control scheme basically maximizes the power production output of local DGs, and optimizes power exchanges between the microgrid and the main power grid.

## IV. Implementation of Multiagent System

The microgrid considered in this paper consists of several autonomous decision making entities, such as PV agent, FC agent, CESS agent, PCBB agent, DG agents, load agents, and CB agents (i.e., circuit breakers). Each agent in the MAS represents a major autonomous component of the microgrid. The agents can monitor and control the corresponding components, as well as they can communicate with other agents. No central control agent is available in the proposed MAS. Each source or load makes decisions locally. This can potentially create a distributed, scalable, and robust control for the microgrid.

The MAS was implemented in JADE, which is an open source multiagent development framework fully implemented in java language. It simplifies the implementation of the agent systems through a middleware that comply with IEEE FIPA specifications and standards. It supports an asynchronous agent-programming model, communication among agents either on the same or different platforms, mobility, security, and many facilities with its great resources and libraries.

JADE provides a directory facilitator (DF) service, which is similar to yellow pages. DF allows agents to register their services, and query the DF to find out what services are offered by other agents, or which agents offer certain services. JADE provides ontology support, and also provides facility to develop user defined ontology. This means that it is possible to define own vocabulary and semantics by user for the content of the messages exchanged among the agents. To implement an MAS control framework, it is necessary to define the functions of each agent according to the characteristics and goals of them. Objectives and responsibilities of each agent in the MAS are discussed in the next Section IV-A.

### *A. Agents Specification*

In this step, specifications of agents in the MAS are defined.

1) *Power-Source Agent:* It is responsible for monitoring, controlling, and negotiating power produced by the corresponding microsource and its ON/OFF status.
2) *Load Agent:* It is capable of monitoring, controlling, and negotiating power level of controllable load and its connection status. It is capable of shedding off based on the available power, especially when microgrid is in islanded mode. The MAS has separate load agents for critical load (CL) agent and non-CL (NCL) agent.
3) *CESS Agent:* It monitors its SOC level and requests power from microsource agents and power grid agent when the SOC level is low based on the local measured information. Local control of CESS determines how much energy is needed to store or supply at every instant.
4) *PCC Agent:* It monitors the grid voltage, phase angle, and frequency, and is responsible for informing the changes in the microgrid status to other agents.
5) *PCBB Agent:* It monitors voltage, current, and power level of the microgrid. Grid agent provides current and voltage reference set points to PCBB agent for deciding whether it needs to draw or supply power from or to the main grid.
6) *Grid Agent:* It is responsible for monitoring and negotiating power from the microsources and exporting or importing power when the microgrid is in a grid-connected mode. Power export or import to or from the main grid is according to the market operation implemented by the third-level control.
7) *CB Agent:* It interacts with the corresponding breaker in the microgrid, and is capable of working as a switch. The circuit breaker agent can lead to connect or disconnect of a generator or load based on control commands.
8) *Bus Agent:* It monitors voltage magnitude and phase angle, and maintains the voltage that does not exceed its limits. The proposed architecture has separate dc and ac bus agents.

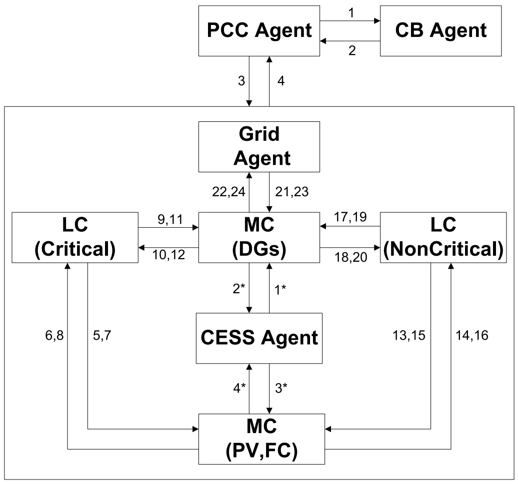


Fig. 5. Agents collaborative diagram.

TABLE I
COORDINATION OF AGENTS

| ID | Collaboration |
|---|---|
| 1 | PCC Agent requests the main CB to turn it On |
| 2 | Acknowledge & Take action |
| 3 | PCC Agent notifies state changes of the microgrid (i.e. grid-connected or islanded mode) to MC, LC, CB and CESS |
| 4 | Acknowledge & Take action |
| 5,7 | CL Agent calls for proposal to PV and FC Agents, Accept/Reject |
| 6,8 | Proposal to CL Agent, Agree or Refuse reply |
| 9,11 | CL Agent requests power to DGs Agent, Accept/Reject |
| 10,12 | Proposal to CL Agent, Agree or Refuse reply |
| 13,15 | NCL Agent calls for proposal to PV and FC Agents, Accept/Reject |
| 14,16 | Proposal to NCL Agent , Agree or Refuse reply |
| 17,19 | NCL Agent requests power to DGs Agent, Accept/Reject |
| 18,20 | Proposal to NCL Agent, Agree or Refuse reply |
| 21,23 | Grid Agent requests/proposes power to DGs Agent, Accept/Reject |
| 22,24 | Proposal/Acceptance to Grid Agent, Agree or Refuse reply |
| 1*/3* | CESS Agent requests power to DGs, PV, FC Agents based on SOC level |
| 2*/4* | Acknowledge & Take action |

9) *MG Agent:* It represents the microgrid model in the MAS.

In addition, the MAS has a distributed database. It is required to keep the messages and data shared among agents, and to maintain a track of each agent. It may also serve as a data access point for the agents.

### B. Agent Roles and Responsibilities

This section provides the defined functions and roles of each agent based on the proposed control architecture. The function of an agent is defined by a set of behaviors. Several behaviors can be executed by an agent. Therefore, each agent has autonomy to perform its goal oriented behaviors. The collaborative diagram of the MAS is shown in Fig. 5.

This illustrates the interaction among agents, and their interaction with the environment. Table I gives a general idea about how these agents are defined, and shows the required messages for the interactions.

The MAS is initialized by registering the agents in DF associated with corresponding services. Therefore, when an agent wants to send a message to another agent, the agent asks from DF to provide a list of agents for the requested service. For example, a load agent will look for the source agents in DF whenever it wants power. After the initialization, all the agents will start performing their functions.

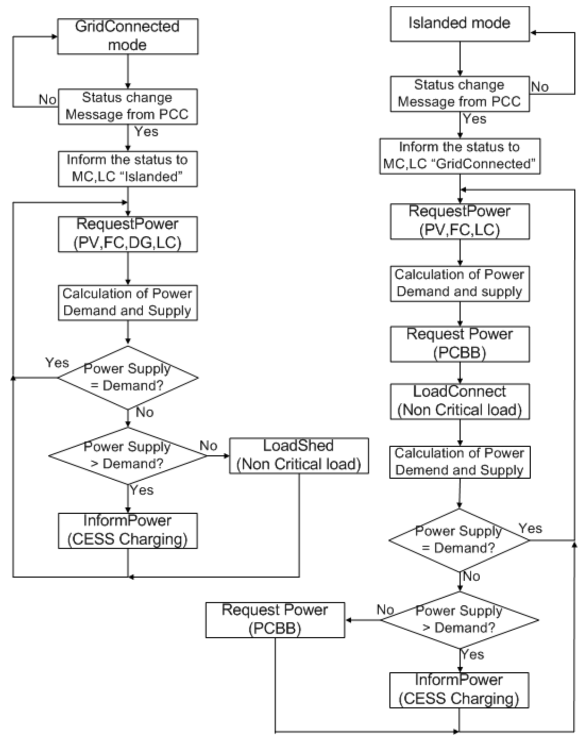


Fig. 6. Rules behind the negotiation among agents.

The agents negotiate among themselves to share the available energy. All discussions among the agents are started by load agents. The load agents request the other agents for a proposal of power supplies. If a suitable proposal is available in the system, they accept the proposal. Power source agents (i.e., PV, FC, and DGs) receive power request from the load agents, and send a proposal of available power that can be provided to the load agents at the time of request. Agents start negotiating among themselves, and take decisions based on their own rules. The typical decisions are which power sources to accept, and what amount of power to provide by the accepted power sources. The logic behind the agent communication is shown in Fig. 6.

Defining an appropriate ontology that specifies the message content of an agent language is an important part of MAS design. Ontology provides a way to share common understanding of information among agents. Agents communicate by exchanging messages, and the ontology is used to structure the messages. Typically, the content of the message complies with the content language [28], [29] and ontology. In this paper, an Ontology for the agents (i.e., MicroGridOntology) has been developed for real-time control of microgrids. This is shown in Fig. 7.

### C. Control System Interface

The MAS for the real-time control of a hybrid microgrid was developed and implemented in JADE platform. The MAS

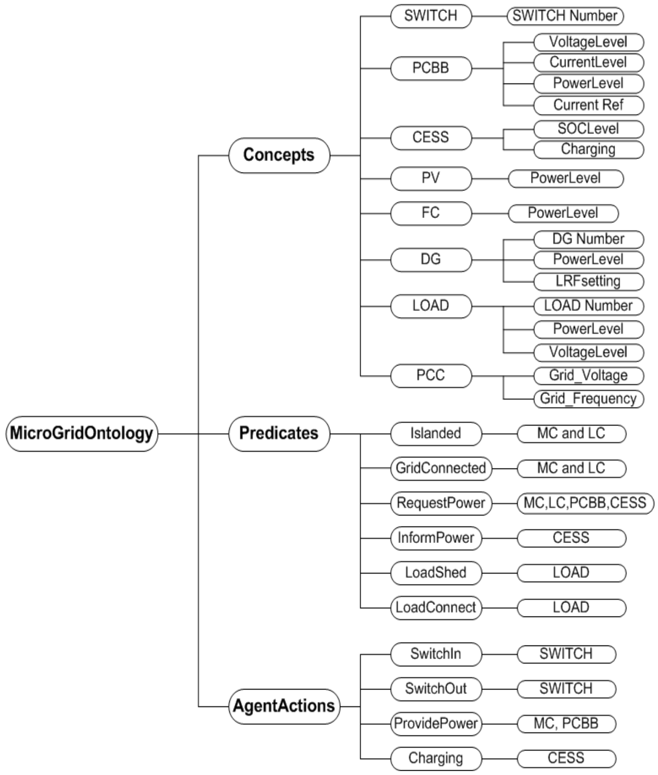


Fig. 7. Ontology for real-time control of microgrids.

and the microgrid model have been interfaced such that it provides a real-time communication channel to exchange messages between them.

## V. Real-Time Control Strategies

According to the proposed three-level control system, the third-level control does short-term scheduling by market operation, which provides scheduling of generating units in 30-min intervals. However, the amount of load and microsources production varies continuously with time. Sometimes these vary from the forecasted values too. Therefore, a real-time control is needed for the operation of microgrid, which must provide new set points to controllable power sources and loads continuously by balancing generation and consumption in real time.

This real-time control can be implemented as a centralized or a distributed system. A distributed control approach for low-voltage power distribution networks potentially offers advantages over a centralized approach in: 1) reliability; 2) scalability and openness; and 3) communication efficiency. The difference between centralized and distributed control approaches is defined by roles and responsibilities taken by the entities in the system. In a centralized control approach, microsources and loads follow the instructions of microgrid central controller, while in a distributed control approach, autonomy for microsources and loads are provided with different objectives and ownerships. Therefore, the distributed control approach is well suited for managing multiple sources and loads in the power distribution system.

According to the distributed approach, the main responsibility is given to the LCs, MCs for sources, and LCs for loads. MCs compete to maximize the production of the corresponding sources in order to satisfy the demand in real time, and LCs do safe and smooth operation of the corresponding controllable loads. The types of power sources considered in the paper are briefly explained as follows.

1) *Controllable Power Sources:* Most of the DGs operating by fuels are fast enough to reset the power outputs. Therefore, they can participate in load-frequency control. CESS also can participate by changing its power production level according to system conditions.
2) *Fixed Power Source:* Due to the characteristics of FC, it is desirable to operate with a constant output power. In this paper, FC is considered as a fixed power source.
3) *Main Grid:* The MAS ensures the power exchange between the microgrid and the main grid. Whether the power is exported to the main grid or imported from the main grid is decided by the third-level control.
4) *Noncontrollable Power:* PV panel is a noncontrollable power source in the microgrid, which is operated together with MPPT concept in both grid-connected and islanded modes.

### *A. Grid-Connected Microgrid*

In a grid-connected mode, the main role of the microgrid is to accommodate: 1) real or reactive power generated by the microsources and 2) load demand. During the grid-connected mode, the frequency of the system is maintained by the main grid. The MAS optimizes the real power outputs of the sources. The main criteria for deciding power sharing among microsources are minimization of operational cost of the sources.

### *B. Islanded Microgrid*

During upstream outage conditions, the microgrid is designed to disconnect itself from the main grid using an intelligent switch. The switch automatically detects any disturbances like faults inside or outside the microgrid by observing frequency and phase angles at the connection points. Reconnection is acceptable if voltage error is $<3\%$, frequency error is $<0.1$ Hz, and phase angle error is $<10^\circ$ [34]. In islanded mode, there is no support from the main grid. Voltage and frequency control, as well as real and reactive power balance should be provided by the microgrid itself. Due to the noncontrollable nature of PV, microsources, such as DGs, FC, and CESS, are responsible for ensuring the power balance by means of absorbing and injecting the power difference between the generation and the local load demand. If available generation is not sufficient to secure all the loads, the least important loads (i.e., NCLs) will be shed.

### *C. Control Algorithm and Power Sharing Scheme*

The MAS reacts to real time changes in the microgrid in 5-min intervals. It overwrites the power settings of the microgrid resources. The execution sequence is described as follows.

1) Each load agent asks the power-source agents for a proposal of power supply.

2) Power-source agents accept the request, and send a proposal according to the available power.
3) Collecting all the proposals and deciding which power sources to accept and at what amount of power.
4) Load agent sends power request to power-source agents based on the individual load requirements.
5) Power-source agent accepts the request, and provides the service by requesting current power level of each source and calculating power adjustments of each source accordingly.
6) Power-source agent sends new power set points to each source. CL agent, NCL agent, grid agent, and CESS agent will also request the needed power from the power-source agent. The power scheduling strategy of power-source agent with multiple DGs is given as follows.
7) Calculate the power difference ($\Delta P_i^{DGT}$) between the generation and the load demand

$$\Delta P_i^{\mathrm{DGT}} = \left(\Delta P_i^{\mathrm{CL}} + \Delta P_i^{\mathrm{NCL}} + \Delta P_i^{\mathrm{Grid}} + \Delta P_i^{\mathrm{CESS}}\right) - \sum_{n=1}^{N} \Delta P_i^{\mathrm{DGn}} \quad (6)$$

where $\Delta_{\mathrm{Pi}}^{\mathrm{CL}}$ is changes in power of the CL, $\Delta_{\mathrm{Pi}}^{\mathrm{NCL}}$ is changes in power of the NCL, $\Delta_{Pi}^{\mathrm{Grid}}$ is changes in power to the grid, $\Delta_{\mathrm{Pi}}^{\mathrm{CESS}}$ is changes in power to the CESS, $\Delta_{\mathrm{Pi}}^{\mathrm{DGn}}$ is changes in power from $n$th DG, $i$ is the time step, and $N$ is number of DGs in the microgrid.
8) Calculate the required power adjustment for each source, which is proportional to their available maximum generation capacities

$$\Delta \mathrm{RP}_i^{\mathrm{DGn}} = \frac{\left(\Delta P_i^{\mathrm{DGn\_}m} - \Delta P_i^{\mathrm{DGn}}\right) \times \Delta P_i^{\mathrm{DGT}}}{\sum_{n=1}^{N}\left(\Delta P_i^{\mathrm{DGn\_}m} - \Delta P_i^{\mathrm{DGn}}\right)} \quad (7)$$

where $P_i^{\mathrm{DGn}}$ is the measured power output of $n$th DG, $P_i^{\mathrm{DGn}-m}$ is the maximum power limit of $n$th DG, and $\Delta \mathrm{RP}_i^{\mathrm{DGn}}$ is the required power adjustment for $n$th DG.

The system has variable energy source such as PVs, and hence it is interesting to show the active power control of the hybrid microgrid system in real time. Active power is considered for all the loads and generators for explanation purpose, however, if the microgrid is connected to the grid both active and reactive power control is necessary for real-time scenarios.

The required power adjustments are calculated for each source, and new power set points will be assigned accordingly.

## VI. Case Studies

The proposed approach was used for the real-time control of a 500-kW hybrid microgrid. The microgrid contains the following distributed sources: a 150-kW PV system, a 60-kW FC, a 65-kW CESS, three synchronous generators whose ratings are 175, 75, and 250 kW, a CL of 375-kW peak, and a NCL of 125-kW peak. The system operates at a rated frequency of 50 Hz. The dc bus voltage is 800 V and ac bus line to line voltage is 400 V. The test system structure for the CASE study is the same as the hybrid microgrid configuration presented in Fig. 1. Simulation studies were carried out on real-time control of the microgrid. In order to make the simulations realistic, historical data of solar irradiation and temperature have been used by the PV model. Further, load demand data are fed into the simulator by collecting real data from a residential area. The power settings of microsource are initially set according to the day-ahead schedule by the third-level control. The three-case studies were carried out for demonstrating the proposed approach and control strategies. Sections III-A–III-C describe these in detail.

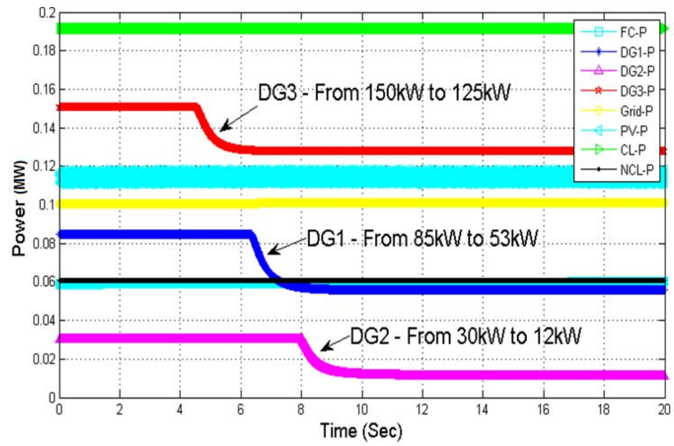


Fig. 8. Results of case 1: fine weather.

### A. Case 1: Fine Weather Condition (13–13:15 h)

First case study was conducted on a typical day. A 15-min interval was chosen to do studies on fine weather condition. In this case, PV system generates high power since the weather is clear and sunny (~100 kW). According to the day-ahead scheduler (i.e., the third-level controller) at time 13 h, FC = 60 kW, DG1 = 85 kW, DG2 = 30 kW, DG3 = 150 kW, and the microgrid supplies 100 kW to the main grid.

However, power demand in the microgrid is low during this period, NCL= 60 kW and CL= 190 kW. Therefore, three is unbalanced power ~75 kW. In order to overcome this unbalanced situation, the agents from the first- and second-level controllers carry out power balancing and provide new power set points for the sources. Fig. 8 shows the results of this case study. It can be seen from the figure that when the demand is low and the power outputs of the sources are needed to reduce from their initial values to operate the microgrid economically.

### B. Case 2: Clouded Weather Condition (13:00–13:15 h)

Second study was conducted on another day. A 15-min interval was chosen to do studies on clouded weather condition. In this case, PV system produces very small power output at 13:00 h since the weather is cloudy. At time = 13:00 h, CESS generates power for the shortfall before the agents (i.e., controllers) take action on it. Fig. 9 shows the output powers of DGs. The output powers of DGs are changed from initial values to new values as agents require getting more power from all DGs.

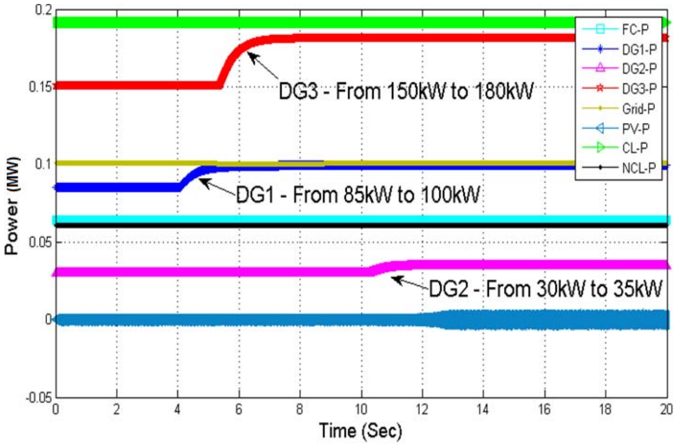


Fig. 9. Results of case 2: clouded weather.

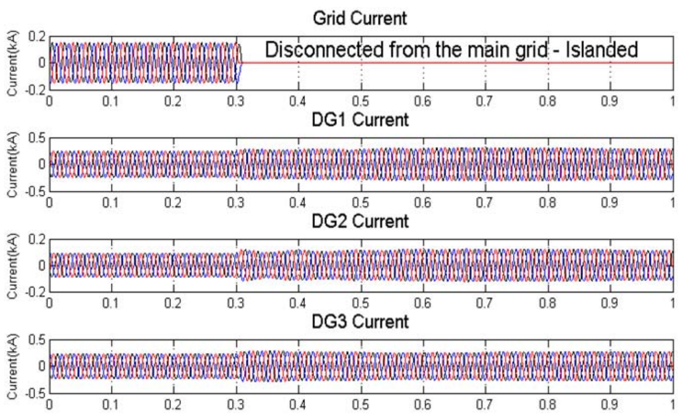


Fig. 10. Variations of grid current and DG currents.

### C. Case 3: Islanded Mode Operation (18:00–18:15 h)

Third study was conducted on a typical day. A 15-min interval was chosen to do studies islanded mode operation of the microgrid. Microgrid has a local load demand of 400 kW (i.e., 300 kW of CL and 100 kW of NCL), and a local generation of 335 kW (i.e., PV = 5 kW, FC = 60 kW, DG1 = 115 kW, DG2 = 45 kW, and DG3 = 110 kW). The system draws 65-kW power from the main grid. At time 18:00 h, a preplanned fault was created at the upstream. Therefore, the microgrid is disconnected from the upstream and operated in islanded mode.

Figs. 10 and 11 show the control actions performed in the system for a preplanned islanding. It can be observed that stability of the microgrid is not lost due to primary control action of the sources. Loss of 65-kW power from the main grid due to the islanding is supplied immediately by three DGs, and the system frequency and the voltage are maintained within their limits. Fig. 11 shows the response of the primary control; the response time of the controller is 1 s, and machine inertia of the DGs may results in slower responses. Allowable voltage variation is 5% and allowable frequency variation is 1% under steady state. During transients such as load shedding/islanded mode, a 3% variation in frequency is considered. In order to restore the system frequency to its reference value, the MAS coordinates for the amount of power required to be fed back, and find out the way of sharing power among the sources in the system.

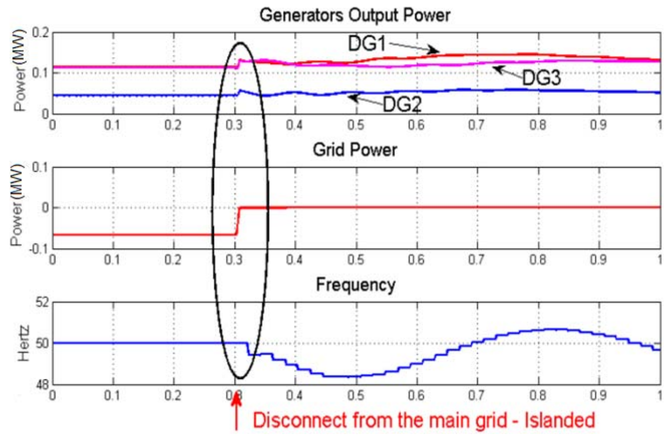


Fig. 11. Preplanned islanding and primary control actions.

## VII. Conclusion

This paper presented an MAS approach for the intelligent control and management of a microgrid. The distributed real-time control system is proposed with droop-based LCs and some deliberative controllers. The proposed control system is implemented on an MAS. Details about the multiagent architecture and the development of the MAS were described in this paper. Further, details about modeling of microgrid and its components are described in this paper. The agents manage the corresponding energy sources and loads according to their individual objectives and goals. The MAS provides a two-way communication channel for all elements in the microgrid. This communication channel is used for cooperative, competitive, and negotiation processes among the entities for the real-time control of the system. To demonstrate the effectiveness of the proposed multiagent-based control system, some case studies were carried out on a hybrid microgrid. Outcomes of the studies show the proposed approach can provide successful performance for the real-time control of microgrids.

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