Multi-agent Microgrid Power Management

C.M. Colson*    M.H. Nehrir*     R.W. Gunderson*

*Montana State University, Bozeman, MT 59717 USA

Abstract: Microgrids are a promising means to broadly integrate distributed energy resource (DER) systems. Seen as an enabling technology within smart grid infrastructure, microgrids offer solutions for both customers and system operators of future power networks. However, the optimal management and control of many generation, load, and storage assets local to a microgrid presents as a daunting challenge. In this paper, an agent-based control architecture for microgrids, capable of coordinating and cooperatively achieving multiple user-defined objectives in real-time is presented. Herein, the authors present fundamental properties required by a decentralized microgrid multi-agent system (MAS), define agent capabilities that support resilient operations, and discuss aspects of the microgrid MAS necessary to smoothly transition between system states. The microgrid MAS developed allows control decision-making to be shifted to a lower hierarchical level, capitalizing on the ability of distributed agents to self-order and cooperate towards an optimal power management solution, given assigned goals. As smart grid technologies continue to evolve, the microgrid operational concepts discussed, along with robust power management and control issues, will play an increasingly significant role.

Keywords: Power management, Multi-agent, Distributed control, Microgrids.

1. INTRODUCTION

There is great uncertainty about how smart grid technologies will emerge and ultimately be implemented. What is certain, however, is that electricity consumption in the United States is projected to grow from 3,873 billion kilowatt-hours in 2008 to 5,021 billion kilowatt-hours in 2035 (EIA, 2010). This increase in electrical energy consumption is dramatic, as are projections of sector demand growth, dominated by increases of 1.55% per year for commercial customers and 0.88% per year for residential customers, sustained over the next three decades (EIA, 2010). Efforts to meet expanding electricity demand are complicated by uncertainty regarding how new generation, transmission, and distribution assets will be implemented in the future. Additionally, concerns about aging power system infrastructure, better integration of distributed energy resource (DER) systems, environmental impacts, energy security, and cost implications further confuse the picture. Despite these questions and the lack of clear direction towards implementation, emerging research on microgrid technology may offer legitimate solutions towards achieving many systematic goals.

Although there is little consensus on a standard definition, for the purpose of this paper, similar to (Kroposki, 2008), a microgrid is specified as a small (typically several MW or less in scale) power system that has three primary components: distributed generators, autonomous load centers, and the ability to operate interconnected with or islanded from the larger utility electrical grid. The interest in the microgrid concept, at the distribution level has been increasing worldwide (Huang, A., 2009) mainly because generation, load, or storage assets connected to microgrids can be coordinated and controlled in a decentralized way (Kojima, 2007). This operational mode allows diverse DER sources to provide their full benefits while reducing the coordination and control burden on the utility grid (Hatziargyriou, 2007). Additionally, as an autonomous power system component, microgrids can reduce the burden on the broader utility power system by taking responsibility for their own operation. The primary goal of microgrid systems is to significantly improve energy production and delivery for local customers, while facilitating a more stable electrical infrastructure with benefits towards environmental emissions, energy conservation, and operational cost.

Distributed control with an agent-based system is seen as an innovative means of achieving capabilities necessary for microgrids to operate effectively. The microgrid control architecture must be fast, adaptable, and resilient to situational and configurational changes. Microgrid assets must be managed in real-time, demanding that optimization schemes show convergence on the order of milliseconds to tens of seconds. The authors’ previous work has indicated that intelligent computational methods may assist agent algorithms in reaching rapid solutions without taxing computational overhead. Similarly, by distributing control functions throughout the microgrid, the system can respond quicker, better maintain continuity of operations, and adapt to conditions as they vary with time. Although communications are an integral enabler for cooperation between distributed control entities, by utilizing autonomous agents, loss or malfunction of communication pathways does not cause the complete failure of control and allows quick recovery.

This paper seeks to address two central issues. First, the power management problem for microgrid systems is explained and why distributed MAS control is applicable to rapidly achieving solutions. Second, a microgrid multi-agent framework, developed with JADE, is proposed having the
capability to achieve power management objectives. This paper is organized as follows: Section 2 provides background on microgrids and their power management. Section 3 introduces the MAS with a specific emphasis on their application towards microgrids. Section 4 shows the development of JADE-based agents for deployment within a microgrid system and Section 5 illustrates how the agents interact through cooperation towards user-defined goals. Finally, conclusions are given in Section 6.

2. DER INTEGRATION, MICROGRIDS, AND POWER MANAGEMENT

Going forward, numerous issues plague decisions about where and how to invest in power system technology. For decades, the traditional model has been to concentrate generation assets centrally and transmit power to distant customers. As the power system grows to meet future demand, this traditional centralized model can incur significant costs for new transmission lines, cause concern regarding system stability, and present challenges for system flexibility. A logical alternative solution to these challenges is to deploy distributed generation systems, which are normally smaller in capacity, adaptable in structure, and installed close to customer load demand. DERs, and specifically generation systems that utilize renewable sources of energy, provide an alternative means to derive electrical power without placing additional pressure on fossil fuel-based supplies. Emerging and existing DER technologies are primarily DC generation sources (e.g. photovoltaics, fuel cells), rectified/inverted high frequency AC sources (e.g. microturbines), variable drive AC sources (e.g. wind turbine doubly-fed induction and permanent magnet synchronous generators), conventional AC generation sources (e.g. diesel), and storage systems (e.g. batteries). Power electronics are typically required to interface DERs, storage, and in some cases load, to the utility grid (Wang, 2007). Experience has shown that the impact of integrating a limited number of DERs onto the grid is not problematic (Walling, 2008). Small DERs in limited deployment are too small in capacity to supply power back to the utility, also known as reverse powering. Likewise, with only one DER generator operating, its power management problem reduces to a trivial one. Investigations have shown the benefits and drawbacks of broader DER integration for conventional power system performance (Sedghisigarchi, 2004) and, overall, uncontrolled connection of DERs to the utility grid is undesirable, especially in large quantities (DeMeo, 2005).

Microgrids, on the other hand, can couple multiple DERs, storage systems, and loads, within a localized framework. Due to their scalable and user-specific implementation, microgrids offer additional system flexibility, including opportunities for combined heat and power (CHP) operations, which can compliment efficiency and service benefits (Colson, 2010). By concentrating these components within a microgrid, it offers a system that is capable of utility interconnection at defined points of common coupling (PCC). This is especially useful from the system operator’s perspective as uncertainties caused by intermittent renewable sources, varying load patterns, and changing storage levels are shifted onto the microgrid operator. This responsibility, therefore, becomes paramount for the microgrid power management and control system to maintain safe, efficient, and reliable functionality. The positive attributes associated with microgrids do come with technological challenges (Basso, 2004). By distributing generation, customer power continuity can improve if microgrids are capable of operating both interconnected with the utility or islanded from it. During normal operations interconnected with the utility, microgrids can provide excess real power and assist in voltage support to the greater power system. When separated from the utility due to abnormal grid conditions (e.g. fault or maintenance conditions), the microgrid must be able to regulate and sustain its own power delivery (Celli, 2004). As highlighted in (Zhenhua, 2009), an interconnected microgrid must, at the very least, comply with grid rules and operate within established power system guidelines. Clearly, microgrids can add value for customer and utility alike; meeting local demand for reliable electricity and reducing strain on utility resources. Ultimately, economic concerns will dictate the exchange of energy services between the microgrid and electrical grid; any viable microgrid power management control architecture must be capable of incorporating these considerations.

The primary purpose of the microgrid power management architecture is to ensure stable delivery of electrical power to its local load customers while optimizing energy production towards an assigned objective(s). Ultimately, key real and reactive power flows on the microgrid are dictated by the generation sources and loads, their system proportion, and how they are operated. The scope of microgrid operational objectives is not limited to simply meeting local power demands, but must optimize towards additional constraints such as: emissions concerns, fuel availability and cost, weather conditions, the spot-market price of electricity, etc. Given the complexity of the problem, there is no clear consensus how microgrid assets should be managed, whether through centralized, decentralized, or hybrid methods. Centralized architectures typically consolidate monitoring and control functions within a single computational center. Conversely, distributed management spreads these functions to a lower hierarchical level, localized to the component or subsystem. Considerations including: quantity and variety of controllers, needed communication infrastructure, specificity of control algorithms, and the interaction between controllers affect architecture formulation. The multi-objective, multi-constraint microgrid power management problem is characteristically more complex than for conventional power system operation, with the following operational attributes.

Major objectives:
- Maximize the customer’s power availability (e.g. meet consumer’s instantaneous load demand).
- Minimize economic factors (e.g. fuel costs, operation and maintenance costs, start-up/shut-down costs, etc.).
- Minimize environmental impact from operating microgrid generators (e.g. emissions, noise, hazardous waste, etc.).
- Maximize the dispatch of schedulable loads (e.g. loads capable of reacting to demand response signals).
- Maximize revenue derived from service delivery to the utility grid (including ancillary services, reserves, etc.).
• Minimize energy purchased from outside microgrid.
• Maximize the total efficiency of the microgrid (e.g. kWhrs generated versus kJ fuel consumed).
• Maximize capitalized energy sources (e.g. operational efficiency of kWhrs available versus kWhrs generated).
• Minimize the frequency of power reversals across the PCC interconnection.
• Minimize transient periods during stabilization in the event of a casualty or interruption.

Minor objectives:
• Maximize load factor (e.g. smooth out the peaks and valleys of load and subsequently required generation).
• Minimize the need for storage assets.
• Maximize the microgrid capability to reduce strain on distribution and transmission assets.
• Maximize VAR support to the greater power system.
• Maximize the reduction in line losses.
• Allow the stable, seamless, and adaptable integration of assets onto the microgrid (also known as “plug-and-play”).

Primary constraints:
• Availability of renewable resources (e.g. solar insolation, wind energy, etc.).
• Bus voltage, frequency, and stability requirements.
• Physical electrical characteristics of the microgrid.
• Status of interconnection.

It is because many microgrid power management objectives can be optimized at a lower hierarchical level (e.g., maximum power point tracking for wind or photovoltaic assets) which encourages interest in microgrid control architecture decentralization. The question arises whether system-level objectives and constraints can be effectively managed by pushing all decision-making to the subsystem level. Many techniques are available to optimize locally, including intelligent methods yielding rapid convergence without large computational expense (Lee, 2008). However, here the authors intend to focus more broadly on how a MAS can cooperatively couple actions of many agent-controlled components to achieve microgrid objectives. In this paper, a subset of the objectives described above will be used, which, it is noted, may at times be in direct conflict with each other. It is believed that MAS techniques can benefit microgrid operations by addressing inherent system complexity in a local and distributed manner.

3. MULTI-AGENT SYSTEMS
A MAS is a collection of autonomous computational entities (agents), which perform tasks based on goals. The agents are granted intelligence; they pursue goals to “optimize” given performance measures in an environment which can be hard to define analytically (Weiss, 1999). An agent can act upon its environment, as well as interact with other agents that may have conflicting goals, towards an common goal. Agents can be imbued with limited or global perception of situational variables, and likewise, each agent’s ability to affect the system environment is dependent on implementation. Although MAS architectures typically use software agents, any collection of computational entities that contains independent agents with the ability to perceive and act upon their environment falls under this concept (McArtur, 2007), and have proven effective in broad applications (Vig, 2006).

Autonomous agents often work with a limited system-wide perspective within MAS architectures, focusing on their assigned tasks and pursuing solutions towards local goals. If data must be passed between agents, the communication means and protocol is important to the MAS implementation. Within the MAS, agents may propose to accept, reject, or counter-propose courses of action based on communication with other agents, but more broadly, agents exchange information about local goal achievement. Throughout operation, autonomous agents comprise the collective command structure and work together. In this way, the microgrid power management problem is an ideal application of the MAS concept, where more capable self-organized and convergent system behavior can emerge from lower hierarchical agent intelligence. The primary advantages of utilizing a MAS structure for microgrids include: dynamic flexibility, asynchronous operation, system survivability, and potentially lower communication overhead. If appropriately formulated, agents may pursue assigned goals despite losing communication with others within the MAS framework. Communication, therefore, can benefit performance, but is not always necessary. Likewise, communication overhead may be an objective to minimize. It is common for local area network or internet protocol communication to be used for MAS implementations (Fakham, 2010) and it is expected that going forward, all available communication protocols including: broadband, power line communications, wireless, and cellular networks, will be used to facilitate MAS interaction. Despite often having conflicting goals, MAS architecture and communications facilitate progress towards common goals while maintaining continuity of operations at a very high level without dependence on a central controller.

4. JADE MULTI-AGENT FRAMEWORK
The Foundation for Intelligent Physical Agents (FIPA) is an IEEE Computer Society standards organization that develops, maintains, and promotes standards for agent-based technology (FIPA, 2010). Standards promulgated by FIPA provide interoperability guidelines and communication protocols that encourage the development of systems that can easily interact. Most importantly, compliance with FIPA standards will likely be necessary before implementation of future MAS systems. The Java Agent DEvelopment Framework (JADE) is a FIPA-compliant platform that specifies a message interaction format that includes performative actions and interaction rules. An example of a market-based microgrid MAS implemented with JADE is shown in (Huang, K., 2009). JADE allows development of unique Java-based agents that can perform a myriad of tasks while interacting with other agents towards achievement of a desired outcome, within a FIPA-compliant framework.

A JADE-based MAS for microgrid power management is a straightforward implementation. Each component or group of components, within the microgrid is implemented with an associated agent. Upon initialization, the Agent Platform (AP) operates autonomously in the background to support the
MAS framework. The microgrid MAS is accessible for communication by other FIPA-compliant platforms, such as from the utility grid, neighboring microgrids, etc. (Bellifemine, 2007). Once initialized, agents attached to microgrid components, or groups of components, can operate independently, according to their programming. The AP directly supports “plug-and-play” connectivity, as agents can come on- and off-line asynchronously and can be easily replicated for fault survivability. Collectively, microgrid agents operate according to user-defined goals and can work independently or cooperatively as their programming dictates, executing their responsibilities in parallel with other agents. Additionally, to support broader parallelism between agent operations, JADE utilizes an event handling concept, called behaviours, to formally dictate how an agent will react to a particular change in state. The concept of behaviours allows JADE agents to more efficiently operate in a real-time environment (Bellifemine, 2007). This attribute allows asynchronous communication, such as the sending and receiving of messages independent of a coordinated clock signal between agents. This, in turn, permits agents to react and cooperate given unpredictable events. In this manner, the agents are not chained to a primary cadence signal or client-server architecture which is characteristic of centralization.

5. MICROGRID MAS DEVELOPMENT

As described above, a given microgrid will operate in two distinct states: interconnected or islanded from a larger utility network. The microgrid power management architecture, formulated as a distributed MAS, must adapt to changing conditions within the distinct context of each state. When interconnected, the agents must control generation, load, and storage assets primarily from the standpoint of power flows. When islanded, voltage and frequency regulation, as well as power balancing, are of critical importance. Within each state, agents seek optimal solutions to assigned objectives, described in Section 2. A challenge facing microgrid MAS design is how to develop capable agents given immense diversity and uncertainty regarding components the customer may choose to connect to a microgrid. Therefore, to simplify the agent framework and encourage better interoperability, all possible microgrid components are segregated into one of four classifications. By classifying microgrid components, the appropriate agent or combination of agents may be assigned to it. For split AC/DC bus microgrid MAS design, the microgrid component classes are:

- **Generation**: capable of sourcing real and/or reactive power.
- **Load**: consumes real power; leading or lagging power factor.
- **Storage**: can source or consume real power.
- **Node**: connection point with measurable electrical quantities.

The microgrid MAS utilizes three basic agent types: the producer, consumer, and observer agents. For each microgrid component, an agent of appropriate type is assigned to it based on class, e.g. producer agent with a generation asset. In the case of a storage asset, both a producer agent and consumer agent are assigned. This is due to the nature of storage assets that appear to the microgrid as a load when charging or a generator when discharging. In either case, the assigned agents negotiate to determine the best operating point for the asset based on objectives. More generally, it would be unwieldy to design a specific agent for each unique microgrid component, and the agent types are kept as general as possible. Subsequently, in terms of agent design, specific agents are not designed for a specific machine or unique load.

The **Producer Agent** has the following responsibilities:
- Monitor available real/reactive power from component.
- Monitor actual real/reactive power supplied by component.
- Determine relative per unit cost of power supplied by component.
- Determine an instantaneous performance measure indicating how well the component is achieving optimal operation.
- Give commands to the component regarding startup, shutdown, and quantity of real and/or reactive power to produce.
- Communicate information to other agents, including the available capacity, the carrying capacity.

The **Consumer Agent** has the following responsibilities:
- Monitor real/reactive power consumed by the component or bank.
- If attached component is controllable (e.g. dump loads) or differentiated vital and non-vital for demand response measures, determine the real/reactive power margin (load pick up/shed).
- Give startup, shutdown, or configurational orders to component.
- Communicate information to other agents, including the carrying consumption, consumption margin available, and requests to bring on or shut off consumption.

The **Observer Agent** has the following responsibilities:
- Monitor specific parameters within the microgrid network (e.g. voltage/frequency levels, breaker positions, fuel tank levels, etc.).
- Communicate information to other agents regarding the status of the node, e.g. within specification or not.

5.1 Agent Interaction and Prioritization

While a key advantage of MAS is inherent communication and cooperation, determining rules for negotiation is challenging. Specifically, when MAS agents engage in cooperative acts, without a supervisory agent, prioritization and task assignment can be difficult. In other words, for an agent collective without a dictated priority, agents must self-organize throughout operations. For the microgrid power management problem, two metrics are proposed for agent prioritization: cost and performance measure. Delivery cost, which is self-explanatory, is a direct representation of the economic value for power produced or consumed at the instant. Producer agents develop delivery cost characteristic curves based on their assigned objectives, similar to Fig. 1. In the case of microgrid generators shown in Fig. 1, the microgrid owner may desire to fully utilize renewable power (photovoltaics) when available. Therefore, the photovoltaic producer agent promulgates a zero cost to the MAS for delivery of its power, above a certain low power threshold. As producer agents provide cost information, other agents within the microgrid MAS can value their own production capabilities and negotiation can arise. In this way, producer agents prioritize themselves within a delivered cost hierarchy and achieve a collective goal based on individual objectives.

A delivered cost measure alone, however, is not adequate to assist agents in determining the optimal collective operation. For example, when the incremental cost for two producer agents is nearly identical, the agents must rely on an additional metric to establish prioritization. Subsequently, each agent determines a performance measure for its
instantaneous operating point based on how well the agent is achieving optimal operation based on its assigned objectives. For a consumer agent, that measure may be a proportion of vital loads are fully powered by the microgrid. In the case of an observer agent whose responsibility is to monitor voltage at a bus, Fig. 2 shows the relative performance measure curve based on the parameter it senses. In the islanded state, each generation, load, or storage asset attached to the microgrid has a direct influence on AC bus voltage. The AC bus observer agent communicates the relative performance of the MAS collective at managing their assets so that voltage is maintained within a deadband. Fig. 2 shows the relatively high performance measure when voltage is within the deadband, a sharp performance measure decline near the deadband edges, and a negative performance when voltage is out of specification. This information helps the MAS identify better solutions to where to operate microgrid assets.

Fig. 1. Agent-developed delivery cost characteristics.

Fig. 2. Observer agent AC bus voltage performance measure.

5.2 Conceptual Microgrid Application

By utilizing these generalized agents in combination, an effective MAS system can be created. A simple example is shown in Fig. 3. In this microgrid, there are three generation sources (wind turbine, photovoltaics, and diesel generator), one load bank (a group of residences), and one storage asset (a lead-acid battery bank). The microgrid AC bus is connected to both the local DC generation and storage assets (by way of an inverter) and the utility grid by way of a PCC breaker. The MAS is comprised of producer agents assigned to each generator; a consumer agent for the residences; a producer and a consumer agent for the lead-acid battery; and observer agents for the AC Bus and PCC breaker nodes. In the interconnected state, each agent manages its assigned asset according to assigned objectives. In this example, the observer agent at the PCC broadcasts information about the status of the PCC breaker and the spot market price of power supplied from the utility. The spot market price helps establish the threshold used by producer agents to determine how much power they will produce at each instant. This process is supported by the characteristic delivery cost curves that producer agents develop for their assigned source, similar to that shown in Fig. 1. As solar and wind conditions permit, the photovoltaic and wind turbine producer agents maximize individual generation based on a lowest delivered cost and export any excess power to the interconnected utility grid. Likewise, the diesel generator may not deliver power at a lower cost when environmental conditions are favourable, so it remains shutdown. If the solar and wind resource diminishes, the delivered cost developed by the producer agent rises and depending on the spot market price, may force the renewable generators offline. At the same time, the diesel producer agent may or may not decide to operate based on its own delivery cost relative to the spot market price. In this way, individual generators can independently, but cooperatively dispatch power based on user-defined objectives. The producer agent associated with the storage asset may not discharge the battery because its associated delivered cost is higher than renewable energy cost and the spot market price. The consumer agent for the storage is less concerned about cost, but instead relies more heavily on battery state of charge (SOC) as a performance measure to determine when charging is necessary. In this way, the storage consumer agent utilizes a performance measure curve similar to Fig. 2 in order to determine when to charge. Likewise, the consumer agent for the residences maximizes its performance measure by maintaining all of its vital loads energized. Non-vital loads are permitted based on cost objectives relative to current clearing price of power. In the interconnected state, the AC bus voltage/frequency observer agent is uninvolved due to the relative electrical rigidity provided by the utility.

Fig. 3. Example microgrid with assigned MAS agents. Dashed lines show communication; solid lines power flow.
In the islanded state, agents operate to maintain continuity of service to local loads. When the PCC breaker opens signalling loss of utility support, the observer agent reports this as an infinitely high spot market price to the microgrid agent. The microgrid clearing price for power now depends on the MAS to determine. Based on the clearing price signal, producer agents seek to maximize local generation. The storage producer agent sees its dispatch priority change due to the rise in spot market price and may discharge. The load consumer agent receives voltage and frequency performance measure information from the AC bus observer agent and responds by incrementally shedding non-vital and then vital loads as necessary to restore the parameters to their deadbands. As the transient loss of the utility interconnection stabilizes, the load consumer agent and the storage producer agent negotiate with cost and performance information from the AC bus observer agent to determine the best battery discharge rate and composition of loads to operate. As conditions fluctuate on the microgrid, the agents react accordingly to best meet their objectives within given limitations.

6. CONCLUSIONS

Microgrid technology may be the strongest opportunity for integrated DER implementation within future power systems. In this paper, the objectives and constraints for the microgrid power management problem have been introduced. To comprehensively address the control and coordination challenges of a multi-asset microgrid, a decentralized MAS is proposed facilitating lower hierarchical level decision-making and the integration of autonomous agents. The multi-agent approach to the microgrid power management problem is greatly complicated by demands for resilient, robust, and rapid solutions, but the MAS proposed here shows promise to overcome control challenges native to microgrid applications.

REFERENCES


