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Survey Paper

Survey of multi-agent systems for microgrid control

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ABSTRACT

Multi-agent systems (MAS) consist of multiple intelligent agents that interact to solve problems that may be beyond the capabilities of a single agent or system. For many years, conceptual MAS designs and architectures have been proposed for applications in power systems and power engineering. With the increasing use and modeling of distributed energy resources for microgrid applications, MAS are well suited to manage the size and complexity of these energy systems. The purpose of this paper is to survey applications of MAS in the control and operation of microgrids. The paper will review MAS concepts, architectures, develop platforms and processes, provide example applications, and discuss limitations.
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1. Introduction

The successful operation of a power system depends largely on its ability to economically and reliably meet load demands of residential, commercial and industrial customers. Early power utilities employed human dispatch operators equipped with supervisory control and data acquisition (SCADA) systems to manage plant control, protective relaying, transmission switching and communication protocols, along with economic operation of large interconnected power plants. While SCADA systems offer timely and detailed monitoring of traditional grid resources, the raw data generated often contains only implicit information. Additional analysis by engineers using multiple data sources is often required to obtain explicit information about power system operations. Such manual analysis of data can be time-consuming. For example, in the event of grid failure SCADA systems can generate thousands of fault records in a matter of only a few hours, real-time manual analysis of which is unfeasible (Davidson et al., 2006).

Autonomous control of power system operations using multi-agent systems (MAS) has been shown to overcome many such limitations (Roche et al., 2010). MAS are composed of multiple intelligent agents that interact to solve problems that may be beyond the capabilities of each individual agent (Weiss, 1999). In recent years, MAS have been employed in a wide range of power system applications including modeling of electricity markets (Weidlich and Veit, 2008a), grid protection (Pang et al., 2010), fault restoration (Nagata and Sasaki, 2002) and grid control (Dimeas and Hatziargyriou, 2007). In 2007, a comprehensive review of MAS for power engineering applications was conducted by the IEEE Power Engineering MAS working group regarding the technologies, standards and tools for building MAS (McArthur et al., 2007a) and concepts, approaches and technical challenges within the field of MAS that are appropriate to power engineering applications (McArthur et al., 2007b).

Recently however, technological advancements, security concerns, regulatory policy and environmental considerations are changing the landscape of electricity generation and transmission by reducing the grid's reliance on large centralized generation facilities. Significant changes to deregulation and competition in the electrical industry over the past two decades led to the emergence of wholesale energy markets reliant on the decentralized decisions of generation firms in contrast to utility based centralized generation units (Ventosa et al., 2005). Consumer demand for clean energy and government regulation is driving the increasing proliferation of distributed energy resources (DERs) like photovoltaics (PV), fuel cells, and wind power into the modern electric grid. After the Northeast blackout of 2003, smaller scale localized generation systems emerged as a key contender in supplementing the existing power system to address the inability of a traditional power systems to provide for growing use of electricity (Marnay and Bailey, 2004). More recently after Hurrican Sandy, several governmental agencies recommended investment in resilent energy resources (Hurricane Sandy Rebuilding Task Force, 2013).

Microgrids have emerged as an effective paradigm to manage DERs. A microgrid is an integrated energy system consisting of

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interconnected loads and distributed energy resources that operates in parallel with the primary power grid, or in a standalone "islanded" mode (Smith, 2010). In the event of a failure, the generation and corresponding loads of the microgrid can be isolated from the distribution system without harming the integrity of the transmission infrastructure. Microgrids help facilitate rapid integration of DERs, offering "plug and play" capabilities without requiring the re-engineering of the distribution system control architecture (Lasseter, 2007). Microgrids are seen as a future power system configuration providing clear economic and environmental benefits. Extensive efforts are in progress across the world to demonstrate microgrid operating concepts in laboratories and in pilot installations (Hatziargyriou et al., 2007). In America alone, the Department of Energy is expected to oversee the development of commercial scale microgrid systems capable of reducing outage time of required loads by over 98% at a cost comparable to non-integrated baseline solutions while reducing emissions by at least 20% and improving energy efficiencies by more than 20% (Bossart, 2012). Reviews of microgrid concepts, operations and applications are available in Lasseter (2007), Jiayi et al. (2008), Zamora and Srivastava (2010), Lidula and Rajapakse (2011), Huang et al. (2010), Ustun et al. (2011), Colson and Nehrir (2009).

The purpose of this paper is to survey applications of MAS in the control and operation of microgrids. Section 2 reviews agent and MAS concepts. Section 3 discusses multiagent interaction and coordination through MAS architectures. Section 4 describes a conceptual process, software tools and platforms (JADE, ZEUS and VOLTTRON) available for developing MAS specifically for microgrid control. Section 5 surveys the literature for demonstrative examples of MAS as an alternative to traditional control of microgrids for applications including market operations, fault location and service restoration. Some limitations of agents and MAS are discussed in Section 6.

2. MAS concepts

An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives (Wooldridge and Jennings, 1995). Agents take sensory input from their environment, produce output actions that affect it (Fig. 1). Agents can be described with several properties:

- *Autonomous*: Agents exert partial control of their actions and internal state, seeking to *influence* outcomes without the intervention of humans or external devices.
- *Social*: Agents can communicate with humans, external devices or other agents to coordinate actions and satisfy their objectives.
- *Reactive*: Agents react in a timely fashion to changes in their environment.

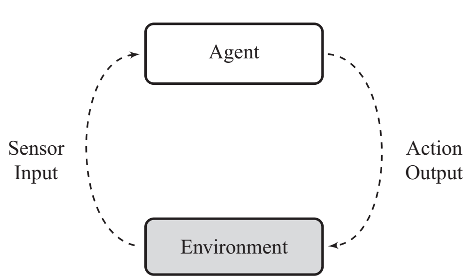

Fig. 1. A simple agent in its environment (Wooldridge and Jennings, 1995).

- *Proactive*: Agents exhibit goal-oriented behaviors and take initiative to satisfy objectives.

Simple reflexive agents react to their environment without cognition of past or anticipation of the future state of the environment. Their reasoning is based on explicit knowledge or models of the environment. Learning agents have the ability to make improvements to their performance element by seeking feedback on their actions and interactions with the environment (Russell et al., 1995).

Sycara (1998) characterized multi-agent systems (MAS) as distributed systems with two or more agents, where:

- Each agent has incomplete information for problem solving. Agents can achieve global objectives through competition, collaboration or other interactions.
- There exists no system for global control. Individual agents can cooperate with other agents in the MAS to achieve individual objectives, or coordinate to maximize global utility.
- Data and environment are decentralized, all agents can affect changes in the environment within their own "spheres of influence".
- Computation is asynchronous, agents can carry their tasks independently without having to wait for a central control signal.

Stone and Veloso (2000) present many example implementations of MAS (Fig. 2). Agents can differ (heterogeneous) or be identical (homogeneous) in goals, actions and domain knowledge. Homogeneous agents differ in sensor inputs and action outputs, hence do not behave identically. Depending on the inputs they receive, each homogeneous agent can make an independent decision regarding their action response. Agents can communicate with each other through a central directory, or can transmit information directly between each other. Non-communicative agents can still affect each other indirectly, either actively through sensor inputs or passively by altering the environment.

MAS allow for the distributed control of microgrids as an alternative to traditional hardware based centralized control. In some domains, the inherent complexity of a system makes it difficult to obtain *a priori* knowledge about potential links between sub-problems. Consider for example, the problem of optimizing the market performance of a grid connected microgrid with multiple consumption units (CU) and production units (PU)

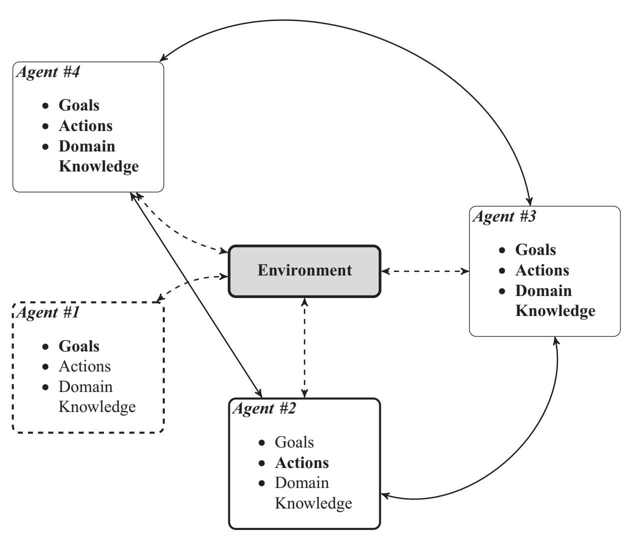

Fig. 2. MAS with homogeneous (#*3* and #*4*), heterogeneous, communicating (#*2* , #*3* and #*4*), and non-communicating (#*1*) agents (Stone and Veloso, 2000).

(Dimeas and Hatziargyriou, 2004). Each CU or PU might have different owners and therefore different objectives. In open market auctions, PUs will try to maximize their profits while CUs will try to minimize the cost of purchasing power. Additionally, the system has a global objective of load balancing at the end of each auction period. Traditional approaches to solving this optimization problem requires the enumeration of all acceptable selling prices (SP) and buying prices (BP) for each individual unit connected to the microgrid. As the number of units in the microgrid increases, solving the problem in real-time becomes difficult.

MAS present an effective way of decomposing complex problems into a number of simpler sub-problems. By modeling each unit as an autonomous agent, each agent attempts to achieve its individual objective of maximizing its utility. When the auction period begins, CU agents actively negotiate with PU agents to meet their load demands. If the initial price bid by the CU agent is rejected by the PU agent, the CU agents make progressively higher bids till their demand price is met by a PU, failing which they autonomously choose to buy energy directly from the grid. The global objective of meeting load demand therefore emerges out of inter-agent collaboration and coordination in real-time. Even in the absence of *a priori* knowledge of the complete system, agents can employ machine learning techniques to learn how to solve problems in a stochastic environment without a central controller (Dimeas and Hatziargyriou, 2010).

A centralized hardware-based control system may need to be redesigned to accommodate structural changes to a microgrid. Agents, however, are independent of their environment. In the earlier example of microgrid market operations (Dimeas and Hatziargyriou, 2004), all CU agents are *homogeneous*, as are PU agents (Fig. 3). The same set of agents programmed for one instance can be deployed for multiple instances without the need for redevelopment. When built on open architectures, agents are programming language and platform independent. Such programmable MAS are easily distributable and offer “plug and play” capabilities, allowing flexibility for future expansion. Consider the problem of service restoration in a microgrid, after a section is isolated due to a fault . Under fault conditions, circuit breakers in a grid system are designed to trip rapidly to isolate and localize the fault. A centralized controller might lack the ability to adapt quickly to such sudden changes in network structure. Xu and Liu (2011) implemented a distributed MAS control system, where each bus of the microgrid is associated with a node agent (NA). Each NA only has access to local generation and load information. An independent infrastructure facilitates inter-agent communication, even in the absence of a distribution line. In the event a fault, individual NAs use the communication infrastructure for global information discovery through local communications with neighboring agents. A composite picture of the entire system is arrived at through interactions of multiple agents with local information. Service to loads in the microgrid can subsequently be restored after all the global information has been discovered. Simulation studies demonstrate the effectiveness of this approach as an alternative to traditional computing algorithms.

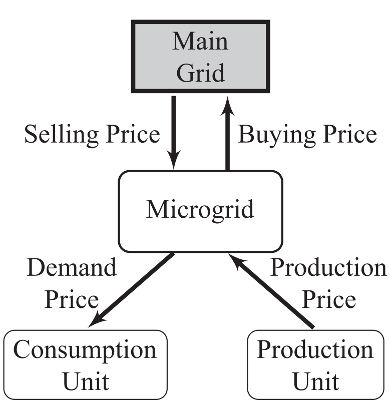

Fig. 3. Market operations of a microgrid using MAS, adapted from Dimeas and Hatziargyriou (2004).

A centralized approach to solving sub-problems in a complex system might have unpredictable outcomes due to the impossible task of modeling all possible interactions and subsequent perturbations. The abstraction of sub-problems into autonomous agents also allows reflexive agents to achieve their design objectives in an asynchronous manner, without waiting for external commands to carry out their tasks. Such a decentralized approach helps faster operation and decision-making process, leading to effective microgrid control in a time-sensitive manner (Colson and Nehrir, 2009). MAS have increased fault tolerance and resiliency owing to redundancy built into the system (McArthur et al., 2007a). The roles of each agent can be masked or duplicated into alternative backup agents that can be called upon to execute objectives in case of agent failure.

3. MAS architecture

MAS may consist of large numbers of agents operating in rapidly evolving dynamic environments. Since data and environment are decentralized, the roles and responsibilities of intelligent agents need to be clearly defined to resolve potential conflicts that may arise through agent interactions. While a conceptual MAS design process is discussed in a later Section 4, a basic structure of a MAS can be broadly classified into the following architectures (see Table 1).

3.1. Centralized

A centralized architecture is characterized as a collection of simple *homogeneous, non-communicative* agents that are managed by a single control center in a master–slave relationship. Such an arrangement closely reflects traditional zone based control strategies with some additional functionality.

Dimeas and Hatziargyriou (2009) describe two classes of agents: reactive and cognitive. Cognitive agents are equipped with increased intelligence and higher-level communication capabilities. The central controller as a cognitive agent communicates with reactive agents and manages the operation of non-critical loads (see Fig. 4). In the event of a power shortage, the central controller disconnects non-important loads. Additionally, some control is also distributed through reactive agents that lack higher-level decision making capabilities. Such agents are used in applications that demand a quick response. In the event of a fault, an under frequency relay with only access to local information can trip a circuit autonomously without coordinating its actions with a central controller. Other implementations of centralized architecture for MAS control of microgrids are available at Dimeas and Hatziargyriou (2004) and Wang et al. (2011).

3.2. Distributed

A distributed architecture is characterized as a collection of *communicative* agents managed by a single layer control structure. Each local agent is responsible for and has knowledge about its own part of the network, indeed no single agent has complete knowledge of the whole domain.

Instead, individual agents are allowed to discover global information through communication and coordination with their

Table 1
Summary of MAS architectures for microgrid control.

Architecture [ref. implementation]	Agent type	Role
Centralized (Dimeas and Hatziargyriou, 2009)	Cognitive Reactive	High level decisions, communication Quick response
Distributed (Jiang, 2006)	Local	Local information discovery, communications
Two-level hierarchical (Oyarzabal et al., 2005)	High-level Low-level	Infrastructure management, inter-microgrid communication, low-level agent scheduling Accept schedules, asset management
Three-level hierarchical (Cossentino et al., 2011)	High-level Mid-level High-level	Critical decisions, data and policy management Fault location, grid-connected/islanded mode switching Sensor management, hardware *I*/*O*

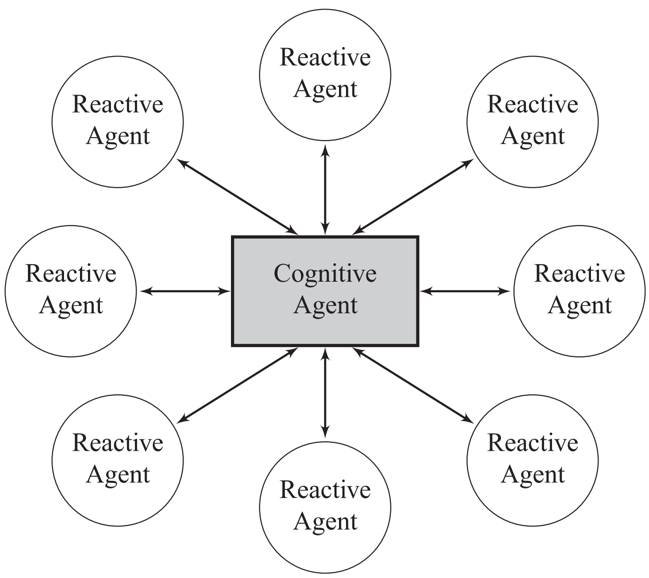

Fig. 4. Generic schematic of a centralized architecture for MAS microgrid control.

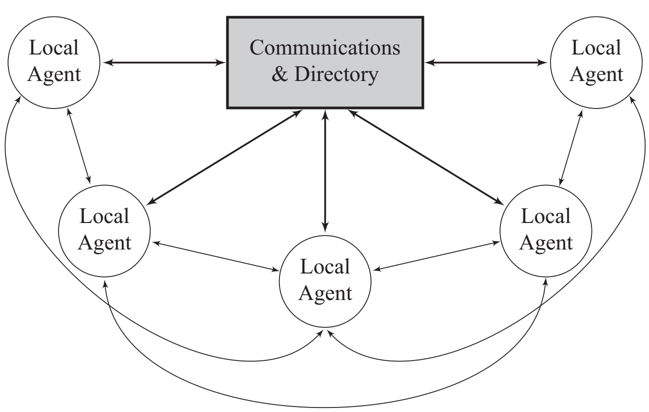

Fig. 5. Generic schematic of a distributed architecture for MAS microgrid control.

neighbors. A single common communication framework facilitates interaction among all agents. In Jiang (2006), the authors propose a distributed system of self-organizing energy source, energy storage and load agents, individual agents can register and publish their capabilities to a directory, from which other agents can evaluate and request services (see Fig. 5). A load agent can look up all available energy source agents and solicit bids for energy supply. Energy agents can communicate with energy storage agents to schedule storage events. The distributed architecture can also help build robust systems with built-in redundancy, with agents being able to re-organize and cope with the loss of other agents.

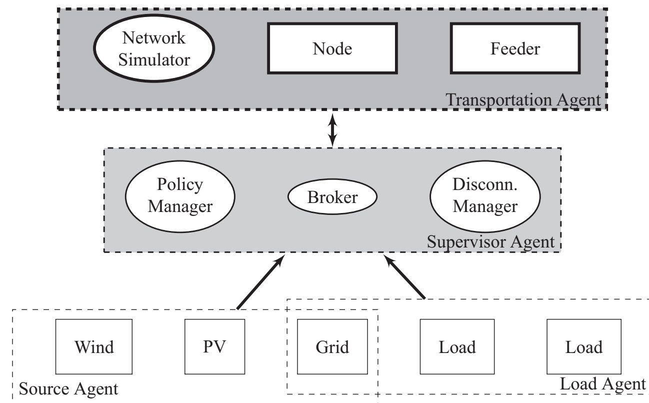

Fig. 6. A three level hierarchal architecture for MAS microgrid control from Cossentino et al. (2011).

Some centralized and distributed MAS architectures may not be able to fully exploit collaboration, competition, consensus building or other advanced functionalities offered by MAS. For example, a load agent in Jiang (2006) can only select from available bids and cannot simultaneously negotiate for competitive prices from many energy source agents. Simple communication protocols only permit one-on-one interactions between individual agents. The absence of such functionality might result in sub-optimal allocation and management of critical resources.

3.3. *Hierarchical*

Hierarchy is characterized by some agents having authority over the actions of other agents (Farag et al., 2011). Most MAS implementation of microgrids in literature employ a three-level hierarchal architecture. Typically, the upper level agents are responsible for critical decisions, handling large amounts of data and maintaining overall policy, communication schedules and protocols. Middle level agents make decisions about switching between grid connected and islanded modes of microgrid operation, minimize losses, direct the actions of sub-agents for fault location and service restoration. The lower level agents interact with actual sensors and devices that are connected to the microgrid. They sense and control components or devices of the microgrid, such as grid breakers, distributed energy, energy storage devices and controllable loads. Such a hierarchy offers good scalability through clear delineation of roles to agents to ensure robust real-time operational control (Xiao et al., 2010). An example of three level architecture is implemented in Cossentino et al. (2011) with self-interested agents managing power flow locally (see Fig. 6). The top level supervisory agent ensures a strategic supervision of brokerage between energy consumers and suppliers, buying or selling from the open market and disconnecting loads and cells in the event of a blackout. The sources agent is a collection of agents regulating power-generating sources in the system with some crossover with the loads agent in the case of batteries. The transportation agent communicates with the top layer to receive and distribute scheduling information, orders connection to or disconnection from the network and also reads real power data from the microgrid. A simulation of this system was shown to perform a dynamic reconfiguration of its structure to quickly redirect energy flow as well as disconnecting loads to protect itself.

In Oyarzabal et al. (2005), the authors propose a framework for MAS-based microgrid control based on a two level hierarchical architecture: the upper level microgrid central controller (MGCC) is responsible for providing basic infrastructure and services and the lower level microgrid agent platform which in turn is comprised of micro-source controller (MSC) and load controller (LC).

MGCC contains individual agents that are responsible for generation scheduling, market bidding, shifting load connection requests, issuing curtailment actions and interfacing with other agents in the system. The MSC tracks changes in active power output and sends power selling bids to the MGCC. The LC registers shiftable and curtailable loads into the system, and is in charge of executing shifting and curtailment commands received from the MGCC. In Dimeas and Hatziargyriou (2004), agents in the MGCC operate in a collaborative mode to maximize the gain of selling energy to the main grid, and in a competitive mode to reduce their individual operating cost. The idea is extended in Dimeas and Hatziargyriou (2005a,b, 2007), Chatzivasiliadis et al. (2008), and Kumar Nunna and Doolla (2013) to include market participation through market operators (MO) and for advanced "plug and play" capabilities of future microgrids, where the agent in the highest level is only involved in decision making process of the most complex tasks (see Fig. 7). Scaling up to even larger systems, multiple microgrids are combined in Zheng and Li (2010) and the merits of using a tree hierarchy structure over having equal agents engaging in a reciprocity relationship is discussed. Other implementations of hierarchal MAS architectures in literature are discussed in Kumar Nunna and Doolla (2013), Karfopoulos et al. (2011), Logenthiran et al. (2011, 2012), Colson et al. (2011a), Eddy and Gooi (2011), Wang et al. (2000), and Jun et al. (2011).

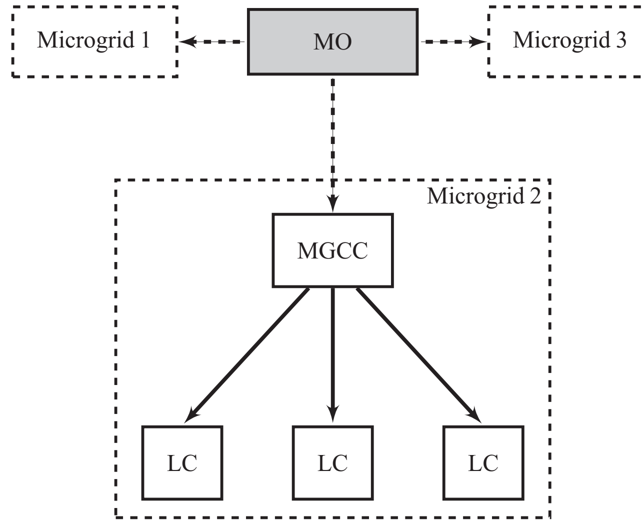

Fig. 7. A two level hierarchal architecture for MAS microgrid control, adapted from Dimeas and Hatziargyriou (2004).

4. Development platforms

A complete description of a conceptual design process for creating MAS is beyond the scope of this paper, but Ricordel and Demazeau (2000) describe a generic four stage development process:

1. *Analysis*: Modeling agent roles and behaviors. Identifying the application domain and problem.
2. *Design*: Defining solution architectures for problems identified in the *Analysis* step
3. *Development*: Programming agent goals, ontology and functionality
4. *Deployment*: Launching generated MAS, run-time agent management, message passing and data processing.

Building a MAS requires an agent development environment that supports at least some stages of the MAS conceptual design process. Comprehensive reviews of several agent development platforms are available in Shakshuki and Jun (2004), Ricordel and Demazeau (2000), Railsback et al. (2006), and Nguyen et al. (2002). This section focuses on platforms most often used by researchers for developing MAS for microgrid control applications. Table 2 provides a summary of the same.

Foundation for Intelligent Physical Agents (1996, FIPA) specifications define rules for the existence, operation and management of generic agents that can be combined to make complex systems. FIPA also allows for the abstraction of the agent development platform from the language used to program the agent, its environment, domain, data and external devices. In order to facilitate communication between agents on different platforms and networks, FIPA also specifies a standard messaging language, agent communication language (ACL), encoded in text. The FIPA reference model (Fig. 8) prescribes the following agents as essential for agent development platforms:

- *Agent management system*: Supervisory platform access, creation, deletion and managing agents on the platform.
- *Agent communication channel*: Inter- and Intra-platform agent communication.
- *Directory facilitator*: Message board service through simple queries. Allows agents to offer and discover services offered by all agents on the platform.

4.1. JADE

JADE (Java Agent Development Environment) is an open source agent development software framework (Bellifemine et al., 1999) for building FIPA compliant MAS. JADE provides tools for building distributable agents across multiple hosts while supporting parallel and concurrent agent activities. JADE supports the *design* and *deployment* stages of the MAS conceptual design process, giving programmers the freedom to abstract agent design. JADE is fully implemented in Java programming language. Additionally, it comes with graphical user interface (GUI) tools for debugging and is freely available for download (TILAB, 1996). Tools for combining Matlab Simulink with the JADE environment are also freely available for research purposes (Robinson et al., 2010). Some examples of MAS for microgrids developed using the JADE agent platform are available in Oyarzabal et al. (2005), Dimeas and Hatziargyriou (2005a), Kumar Nunna and Doolla (2013), Logenthiran et al. (2008, 2011), Colson et al. (2011a), Wu and Zhou (2014), Gooi et al. (2015), Kouluri and Pandey (2011), Aung et al. (2010), Rivera et al. (2014), Leng and Polmai (2013), Gomes et al. (2014).

Table 2
Summary of key differences between JADE, ZEUS and VOLTTRON MAS development platforms.

Properties	JADE	ZEUS	VOLTTRON
Free and open source	Yes	Yes	Yes
FIPA compliant	Yes	Yes	No
Editor	Command line	GUI	Command line
Platform support	Active. Updated December 2014	Discontinued	Active. Updated April 2015
Programming language	Java based	Java based	Programming language independent
Advantages	Stable platform	Ease of development	Hardware driver support
Disadvantages	Challenging for new developers	Weak documentation	Limited industry adoption
Ideal application	Scalable microgrids	Rapid prototyping	Building energy management

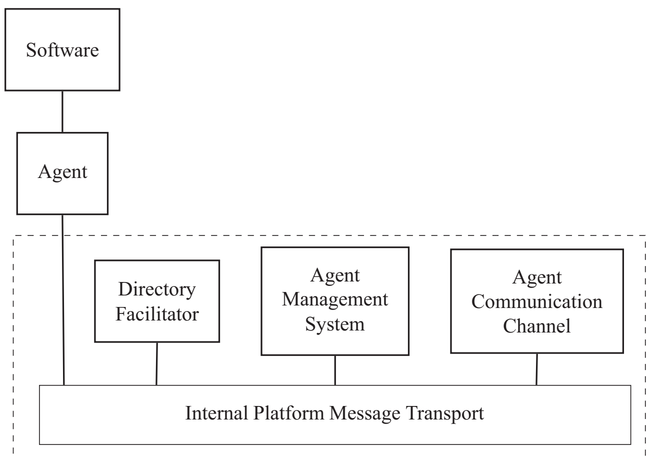

Fig. 8. FIPA reference model of an agent platform, as described in Bellifemine et al. (2001).

4.2. ZEUS

ZEUS (Nwana et al., 1999) is a FIPA compliant open source agent development platform implemented in the Java programming language. It provides users with a graphical user interface (GUI) and a runtime environment. Along with ACL support for agent communication under FIPA compliance, ZEUS also supports knowledge query and manipulation language (KQML) based communication. ZEUS supports all stages of the MAS conceptual design process and is freely available to download for research purposes (British Telecom Intelligent System Research Laboratory, 1999).

ZEUS allows the modeling of agent roles using combination of class diagrams and predefined roles common in most management systems. This design environment restricts the need for developing new formalism, thereby making MAS development more accessible to a wider audience (Ricordel and Demazeau, 2000). Additionally, ZEUS also provides a runtime environment, and various assistant tools for debugging, observing coordination strategies, general purpose planing and process scheduling.

Despite these advantages, new developers might face some challenges in creating new applications using the ZEUS platform owing to weak documentation (Nguyen et al., 2002). Some examples of MAS developed for microgrids using the ZEUS agent platform are available in Xiao et al. (2010) and Li et al. (2010a).

4.3. VOLTTRON

VOLTTRON (Akyol et al., 2012) is a distributed agent execution framework designed by Pacific Northwest National Laboratory (PNNL) specifically for use in electrical power systems. The open source and modular platform is intended to support transactions between networked entities over the grid. Communication is established through a central "MessageBus" in the form of topics and subtopics (for example, "topic/subtopic/subtopic/" = "weather/location/temperature/"). The control architecture is modeled as a three-level hierarchy of agent classes:

- *Cloud agent*: Publishing data to and from a remote platform.
- *Control agent*: Interact with devices.
- *Passive agent*: Interact with sensors and record data.

A combination of agent classes can be employed to derive a variety of agents, and the VOLTTRON development page on Github provides clear examples (PNNL, 2014). While a prototype implementation of VOLTTRON is available in Python, the platform is programming-language agnostic. VOLTTRON also provides driver support for most Modbus (IDA Modbus, 2004) and BACnet (Bushby, 1997) devices.

4.4. Discussion

Several other MAS platforms exist but were not included for comparison because they have not been actively updated recently, e.g., Aglets (IBM Tokyo Research Laboratory, 2004), or not used within the power domain, e.g., SkeletonAgent (Camacho et al., 2005).

The MAS described in a majority of papers surveyed here were built using the JADE platform. Studies evaluating various MAS development toolkits (Shakshuki and Jun, 2004; Sánchez López et al., 2010) have shown that JADE can be used to build robust, complex and scalable MAS for most applications.

Some reviews (Ricordel and Demazeau, 2000; Nowostawski et al., 2000) of agent development platforms suggest that the GUI of ZEUS, along with tools like report generation, statistical analysis and debugging make it a user friendly development environment for rapidly building scalable and distributable MAS, especially for beginners unfamiliar with the agent design paradigm. The same reviews also suggest that the ease of use may come at the cost of lost functionality. Experienced programmers might find it easier to customize or debug the Java language of JADE agent code over fine-tuning the GUI controls of ZEUS.

As a relatively new and continually evolving platform, adoption of VOLTTRON for MAS control of microgrids in research and industrial applications is currently limited, compared to widespread use JADE or ZEUS. However, the open source development platform, broad driver support and programming language independence allows developers to prototype and demonstrate MAS control of grid devices even without access to testing hardware. VOLTTRON will transition from a Department of Energy supported project to the Transactional Energy Consortium for continued development (e.g., integration with GridLAB-D, Pacific Northwest National Laboratory, 2012).

In summary, JADE is best suited for advanced developers building stable and scalable MAS control for microgrids. ZEUS could be best employed by new developers for rapid prototyping and testing of MAS concepts for microgrid control. VOLTTRON is best employed by facilities and building managers for managing sensor and instrumentation data.

5. Applications of MAS in microgrids

The Consortium for Electric Reliability Technology Solutions (CERTS) identifies some key issues in the control of microgrids (Lasseter et al., 2002):

- Addition of new microsources without modification of existing equipment.
- Connect or isolate from the grid in a rapid and seamless fashion.
- Reactive and active power can be independently controlled, voltage sag and system imbalances can be corrected.
- Microgrids can meet the larger grid's load dynamics requirements.

Traditional centralized control infrastructures for microgrids with many devices may incur large costs in communication infrastructure and complexity of the centralized control supervisor. Alternatively, an autonomous local controller acts on local events using local information. This may lead to “more customized local control systems for uniquely different utilities in the system giving greater control over real time operation of a microgrid” (Colson and Nehrir, 2009). Indeed, “local information plus communication produces global control” (Ygge and Akkermans, 1999). The characteristics of MAS discussed in Section 2 lend themselves very well to microgrid control application in the context of Market Operation, Fault Location and Service Restoration.

5.1. Market operations

Significant changes to deregulation and competition in the electrical industry over the past two decades has led to the emergence of wholesale energy markets reliant on the decentralized decisions of generation firms in contrast to utility based centralized generation units (Ventosa et al., 2005). As electricity markets continue to evolve, fully functioning markets are distinguished by the presence of a large number of utility companies, power brokers, load aggregators and marketers that are in direct competition. Market forces drive individual participants to develop their own unique business strategy, risk preference and decision models. Such detailed and complex economic systems cannot be adequately analyzed by conventional models that utilize a single decision maker and a global objective for the entire system (North et al., 2002). The wholesale market is a dynamic network of fuel, resource forecast, bilateral and auxiliary markets. The limitations of traditional modeling methods in dealing with the added complexity of real time demand and supply optimization, transmission limits and unit commitment constraints has been shown to be overcome by agent based simulation models (Weidlich and Veit, 2008b).

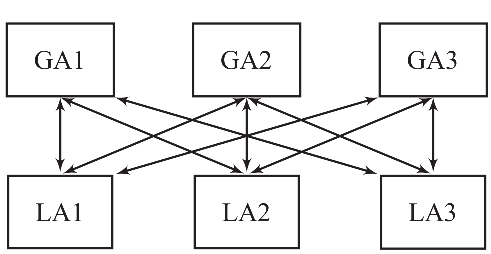

Fig. 9. Auction based mechanism using simple bilateral contracts between generator (GA) and load agents (LA), adapted from Duan and Deconinck (2009).

Agents facilitate distinct players in real-time markets to optimize their performance by maximizing their individual utility through an auction-based mechanism. A typical strategy is to establish bilateral contracts between buyers and sellers in the market. During the negotiation period, a buyer sends out a request with price expectations to all the sellers in the market, and the sellers respond with a price based on availability, system and transmission costs. In Duan and Deconinck (2009), generator agents (GA) interact with their affiliated distributed energy resource (DER) determine unit operation, fuel and maintenance cost along with preferred markup. Load agents (LA) determine the maximum unit price it is willing to pay for a quantity of power required during a specific period of time. GA try to maximize their profits by selling energy above the production costs while LA try to minimize costs by purchasing energy below unit price. The proposed method implements simple bilateral contracts between LA and GA that guarantee energy allocations through competitive bidding (see Fig. 9).

Another strategy is to establish a market operator that sends out a request for bids to all agents in the system at the start of each negotiating period. The market operator subsequently processes the bids, establishes market price and matches the buyers with the sellers (Praça et al., 2003). A MAS system that maximizes revenue of a microgrid in the power markets is discussed by Funabashi et al. (2008). The proposed method consists of several loads agents (LAGs), generator agents (GAGs) and a single microgrid control agent (MAG) implemented in a three-level hierarchical architecture. The GAGs participate in the supply side regulating the operation of the generators, the LAGs operate on the demand side creating agents for buying power from the microgrid. MAG is responsible for optimizing the operation of the microgrid using a negotiation algorithm that selects seller/buyer pairs based on the lowest internal selling price and the highest internal buying price respectively (see Fig. 10). When a conflict arises, the biggest generation reserve and the heaviest load demands are selected as a seller/buyer pair respectively. A large number of simulations over varying testing conditions were shown to have promising results. A more detailed description of a similar architecture including the software implementation is discussed in Dimeas and Hatziargyriou (2004). Preliminary results from the testing of the MAS on a laboratory microgrid demonstrated the feasibility of the approach.

In addition to maximizing the utility of individual players, microgrids operating in real-time power markets may need to satisfy additional objectives: emission and noise levels, operational costs, electricity prices, intermittent and non-dispatchable renewable energy integration, storage scheduling, etc. Decentralized control using MAS may offer flexibility in solving such multi-objective optimization problems. Individual agents with local information acting in self-interest can also co-operate to achieve

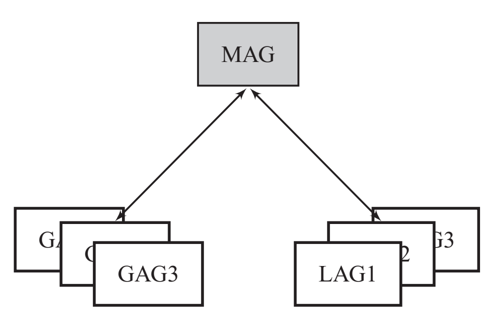

Fig. 10. Auction based mechanism using a market operator with microgrid control agent (MAG), generator agents (GAGs), and load agents (LAGs), adapted from Funabashi et al. (2008).

mutually beneficial goals. Two scenarios investigated in Colson and Hashem Nehrir (2013) using a test microgrid with DERs, storage, diesel generator and loads illustrate the benefits of such an approach. Disturbances are introduced in the stable operation of a microgrid in the form of a rapid change in spot market prices, and sudden loss of solar resource. The microgrid was shown to be able to meet load demand through the co-operation of the generation, storage and PV agents. In addition to changing operational scenarios, collaborative decision making by individual agents was also shown to adapt to changing user defined goals and objectives (Colson et al., 2014).

Market-driven management of distributed, micro storage devices is considered by Vytelingum et al. (2010). The authors cast the problem as a multi-player game showing that the Nash equilibrium is equivalent to the minimizing the total electricity generation cost achieved by reducing expensive peak demand power. Nazif Faqiry et al. (2014) use a genetic algorithm approach to investigate energy trading patterns for a microgrid using renewable generation. The ability to schedule loads is exploited in conjunction with a an optimization cost function that monetizes consumer satisfaction. Trinklein et al. (2014) consider the value stream associated with networked microgrids. They illustrate that a mutually beneficial solution between microgrid owners and utilities may be achieved. This is accomplished by managing the network's aggregated load such that it does not add to peak demand during nominal operation and could provide regulation reserve.

With the advent of increasingly efficient consumer storage devices, demand side units can be modeled as proactive agents participating in open electricity markets with the intent to lower peak demand thereby reducing the need for expensive peaking generators, lowering both carbon emissions and consumer energy costs (Vytelingum et al., 2010). MAS have been shown to handle network constraints that exist in real world electricity markets, by acting in collaboration with "smart" meters installed at the consumer end (Hommelberg et al., 2007). Regulatory agencies appointed to manage competitive electric markets, preserve security of supply, enhance privatization of supply and ensure overall system efficiency have used agent based simulations to analyze market design policy issues for electricity markets (Bunn and Oliveira, 2003).

A comprehensive review of electricity market modeling literature (Sensfuß et al., 2007) shows that the concept of agent based simulation as a test bed for the electricity sector can provide additional insights for market and policy design. Other recent implementations of MAS for microgrid market operations are given in Kumar Nunna and Doolla (2013), Gooi et al. (2015), Gomes et al. (2014), Kim et al. (2010, 2012), Mashhour and Moghaddas-Tafreshi (2009), Kim and Kinoshita (2009), Ghazvini et al. (2014), Nagata and Okamoto (2014a,b), and Zhao et al. (2015).

5.2. Microgrid protection

Microgrids consist of a distribution network that connects several generation units including PV, wind, fuel cells, combined heat and power (CHP) units, microturbines and distributed storage units that improve the performance of a microgrid by damping peak surges in electricity demand, countering momentary power disturbances, providing outage ride-through while backup generators respond, and reserving energy for future demand (Duncan Glover et al., 2011). The radial distribution network with a central power source undergoes a topological change into a new complex architecture when distributed generation (DG) is added. With a large short circuit capacity, a more complex fault current path, variation in dynamic response of the network and the unpredictable output power characteristics of dynamic DG units might render traditional over-current protection schemes ineffective (Wei et al., 2010).

Protection must be extended to the microgrid in its two modes of operation, when connected to the distribution network and in islanded mode. When a fault is discovered in the upstream network, the microgrid is disconnected from the distribution network, and must control its voltage and frequency, provide instantaneous real power difference between generation and loads, provide the difference between generated reactive power and the actual reactive power consumed by the load to protect the internal microgrid. In the islanded mode, frequency control of units like micro-turbines and fuels cells is a challenging problem due to their slow response to control signals. The frequency control strategy should exploit in a cooperative way the capabilities of the micro-sources to change their active power, load shedding or activating storage systems (Kroposki et al., 2008). Several MAS approaches have been proposed to detect faults in a real-time operation of a distribution network and subsequent disconnection and isolation of microgrids from the network.

Alwala et al. (2012) implement a three level hierarchal architecture (Section 3.3) for MAS with two classes of agents: the upper level recloser agents (RA), a lower level zonal agent (ZA) and switch agent (SA) (see Fig. 11). The two classes of agents can coordinate to locate and isolate faults in a microgrid based on sequence current magnitudes and current direction reversal during a fault. RA monitors the status of reclosers at each substation. ZA has local information such as power flow and sequence current magnitude and phase angle of all the distribution lines in their respective. Each ZA has a single SA associated with that zone. When a permanent fault occurs in the system, RA issues a lockout signal to the lower level ZA which then initiates a fault location algorithm through its associated SA. Each SA checks its zone for sequence current reversal or residual current magnitude in all lines that are connected to the violating line. An alternate method for identifying faults is also presented where nodes with no two-way power flows are identified as faulty. Thus, while fault identification occurs at the upper RA level, fault location happens at the lower ZA and SA levels.

Pipattanasomporn et al. (2009) implement a two level hierarchy MAS to disconnect and stabilize the microgrid from the local utility when upstream outages are detected (see Fig. 12). The authors described system with four classes of agents, namely a

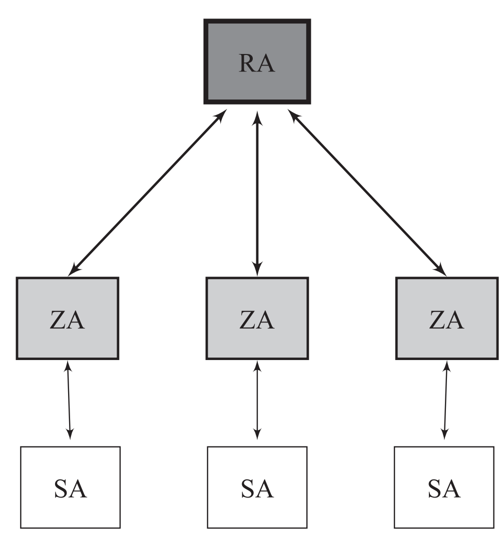

Fig. 11. A three level MAS hierarchy for fault discovery and location in a MAS with recloser (RA), zonal (ZA), and switch agents (SA), as implemented in Alwala et al. (2012).

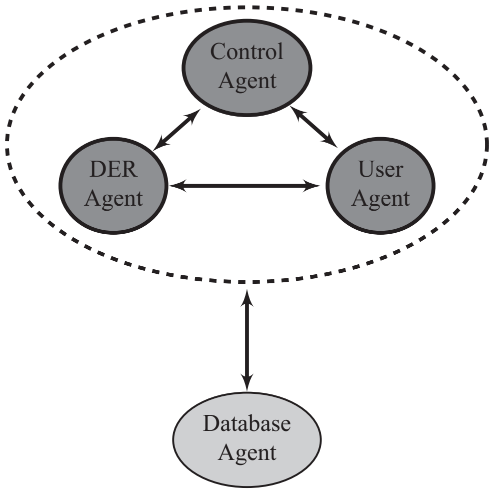

Fig. 12. A two level MAS hierarchy for fault discovery and location in a MAS, as implemented in Pipattanasomporn et al. (2009).

control agent, a DG agent, a user agent and a database agent. In grid connected mode, the control agent in communication with the user agent and the DG agent determine the amount of loads to be shed and the amount of power to be produced internally in order to stabilize the microgrid. All agent actions – from detecting the fault, disconnecting the main circuit breaker, disconnecting the non-critical loads to stabilizing the grid require half an electrical cycle. The control agent also drives the microgrid into the islanded mode by disconnecting the main circuit breaker. In islanded mode, the user agent and the DER agent balance the demand and supply by controlling the voltage and frequency at prescribed limits.

In Ma et al. (2009), generic agents manage relays and communicate through standard Ethernet protocols which are independent of network topology, thereby providing a scalable and dynamic approach for protecting distributed networks. In the event of a critical failure in a distribution line, such an independent communication infrastructure allows agents to continue interaction with other agents on the distributed MAS. The generic agents can also be copied into different components such as switches, breakers and other protection devices, building robust systems with built in redundancy that are resilient to single point fault failure. Examples of MAS for microgrid protection applications are also available in Leng and Polmai (2013), Boussaada et al. (2014), Wu and Gu (2009), Jian et al. (2009), Mao et al. (2014), Kato et al. (2014), and Kulasekera et al. (2012).

5.3. Service restoration

After a fault has been located and cleared, it is essential to restore a system to its operational efficiency. Several approaches to using MAS in distributed power systems are proposed in the literature (Nagata and Sasaki, 2002; Chen et al., 2013; Lim et al., 2013; Solanki et al., 2007; Lo et al., 2009) indicating that for fault detection, isolation and service restoration, MAS could provide an alternative to a centralized processing system.

MAS are particularly more useful in microgrid applications owing to the complexity of the large networks of distributed energy resources, loads and storage units that preclude centralized control. In Colson et al. (2011b), the authors describe a MAS architecture that strikes a balance between the intra-microgrid objectives defined by local operator and the situational demands of the microgrid collective. Under normal operating conditions, agents operate under self-interest by maintaining power to the local vital loads at all times and will seek to export any excess power to other microgrids through communication with other local agents. In an emergency condition, after a fault is located and isolated, the agents begin the restorative phase by shedding non-vital loads and transmit surplus requests seeking additional power. Agents are capable of negotiating temporary power contracts during which the microgrids with excess generation pair with those that have shed load during the emergency. The MAS transitions to a normal operating condition under new network topology, while periodically checking to see if the emergency condition has been rectified.

In Li et al. (2010b), the authors discuss a three layer MAS architecture that can overcome the static constraints (active power balance, reactive power abundance and power flow) on maximizing microgrid fault restoration. When a fault occurs, the lower-level load agents (LA) and local agents (SWA) communicate with a distributed generation agent (DGA), which calculates available transfer capacity and requests additional support from the middle level microgrid agent (MGA). MGA communication protocols are overseen by the higher level central control agent (CA). Multiple MGAs then coordinate efforts into optimizing load restoration by communicating their branch maximum transmission capacity and prioritizing the removal of the most non-critical loads designed to restore proper equilibrium to the microgrid with least load loss.

In Xu and Liu (2011), the authors propose a novel MAS where each agent makes synchronized load restoration decisions according to global information discovery through local communication. Each node agent only has knowledge of local generation and load information but no access to global information. During the information discovery process, agents only communicate with their direct neighbors, and the global information is discovered based on the average-consensus theorem. Each agent is initialized with a matrix whose elements indicate the connection status of various generators and loads. Through application of average-distance algorithm to each corresponding elements of all information matrices, required information for restoration can be obtained. Theoretically, the proposed load restoration algorithm can be applied to systems of any size and structure. Authors in Liang et al. (2012) propose using wireless networks for communication and information discovery in microgrids for consensus based service restoration. Wireless communication between agents was shown to facilitate microgrid monitoring and service restoration at a high flexibility and low cost. Other applications of MAS for microgrid service restoration are available in Rivera et al. (2014), Cai et al. (2011), and Chouhan et al. (2013).

6. Benefits and limitations of MAS

Several of the advantages of MAS for power system applications are again emphasized. These advantages pay particular attention to the expansion of distributed energy resources and the incorporation of renewable sources.

- *Distributed architecture*: The nature of the distributed generation fits into the MAS architecture schemes that rely on local information and decision making.
- *Flexibility*: MAS enable flexibility in several ways: “plug and play” capabilities to change the system and heterogeneous types of agents modeling heterogenous sources and loads.
- *Resiliency*: MAS can quickly respond and adjust to faults. Additionally, changes in network topology (a load or generator being disconnected) will not interrupt both local and global system objectives (e.g., stability and efficiency).

Wooldridge and Jennings (1998) identified general pitfalls in developing agent oriented processes. Challenges in using MAS for power system applications were reviewed in McArthur et al.

(2007a). As with any emerging research paradigm, MAS control of microgrids faces some limitations that impede widespread adoption. Each of these limitations are also opportunities for future research directions.

- *Emergent behavior*: The autonomous and distributed nature of agents might lead to unpredictable outcomes. While the goals and objectives of agents can be programmed, the effect of run-time interactions cannot always be pre-determined (Jennings, 2000). This sort of emergent behavior might be beneficial under some circumstances (e.g., market operations), but inherent uncertainty may be a drawback in some applications (e.g., service restoration).
- *Portability*: Hardware implementation of conceptual MAS designs and architectures can be challenging. Most current implementations of MAS control of microgrids are software simulations, e.g., virtual MATLAB Simulink testbed, and the performance of many MAS approaches on actual microgrid hardware is yet to be widely tested.
- *Scalability*: Greater computational power available these days allows researchers to model larger microgrids with many agents coordinating actions on a single platform. However, the ability of MAS to scale (Rana and Stout, 2000) with increases in problem dimensions (agents across multiple *platforms*) or diversity (agents of multiple *types*) is not well understood.
- *Security*: The shift from largely physical infrastructure towards smarter technology increases the risk of security and privacy violations from malicious external actors and disruptive elements.

7. Conclusions and future trends

This paper introduced the theory and concepts that make multi-agent systems (MAS) well suited for the operation and control of microgrids. Agent interaction, coordination and cooperation was discussed in the context of MAS design architectures. A step-by-step conceptual framework and platforms for building MAS were introduced. The application of MAS in microgrids for market operations, fault identification, fault location and service restoration was reviewed with demonstrative examples from literature.

Microgrids are expected to be an integral part of the electricity grid of the future offering improved resiliency, integration of DERs, bi-directional vehicle charging, advanced storage and demand management (Manz et al., 2014).

As greater computational power becomes more available, researchers are able to model increasingly complex interconnected microgrids. In simulations, MAS were shown to scale to microgrids with thousands of interconnected generators, loads, buses, breakers, reclosers and other grid elements (Alwala et al., 2012). Improvement in forecast models will lead to better prediction of load demand in disaggregated environments over shorter time horizons (Hernandez et al., 2014). Agent communications continue to evolve by adapting to changing grid communication protocols leading to improved agent consensus building, faster response time and adaptability (Farid, 2015). Standardization of MAS architecture and practices will lead to greater system interoperability in the microgrid and smart grid environment.

The inherent uncertainty of software complexity, hardware incompatibility and security risk to malicious external actors limit widespread adoption of MAS for the control of microgrids. A true test of MAS applications for microgrid control can only come from rigorous field tests of hardware prototypes from multiple developers and vendors.

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