Design of an Intelligent Self-Healing Smart Grid using a Hybrid Multi-Agent Framework

Darmawan Sutanto, Da-Yong Ye, and Min-Jie Zhang

Abstract—This paper discusses the applications of a hybrid multi-agent framework for self-healing applications in an intelligent smart grid system following catastrophic disturbances such as loss of generators or during system fault. The proposed hybrid multi-agent framework is a hybrid of both centralized and decentralized scheme to allow distributed intelligent agent in the smart grid system to make fast local decision while allowing the slower central controller to judge the effectiveness of the decision made by the local agents and to suggest more optimal solutions.

Index Terms—Intelligent agent, multi-agent, power system, self-healing, smart grid.

1. Introduction

Electricity industries are being transformed worldwide, driven by the need for more energy, urbanization, scarcity of natural resources and global warming. One of the most promising technologies is the smart grid technology which combines a traditional electric power grid with an “intelligent” information and communications technology (ICT) infrastructure to produce a smarter power system. This is achieved by having a large number of sensors, two-way communications and data acquisition system to provide real-time monitoring, diagnosis and control. This will enable the electricity grid to be observable (able to be measured and visualized), controllable (able to manipulated and optimized), automated (able to adapt and self-heal), and fully integrated (fully interoperable with existing systems and with the capacity to incorporate a diverse set of energy sources)[1].

One of the potential applications of the smart grid is the self-healing capability during emergency condition associated with catastrophic disturbances.

Outages and faults will cause serious problems and/or failures in interconnected power systems. Unfortunately, most system outages and faults are inevitable[2]. Even though technologies can be employed to estimate future possible faults in power systems[3], sources of vulnerability such as human errors, control system failures, missing information in decision making, and communication network failures will also threaten the system safety. Without considering effective countermeasures for faults and failures, small errors will also generate catastrophic failures and cascading sequences of events. For example, the incorrect settings of protective devices and control strategies could not successfully interrupt cascading events, so caused the August 10, 1996 WSCC system outage[4].

Due to the complexities and expanding structures of present day power systems, conventional centralized and regulated control systems tend to be inadequate because of deficiencies in robustness, openness, and flexibility. Furthermore, centralized control systems are highly sensitive to system failures because the control system relies on single decision-making software component or human operators.

In an electricity network, catastrophic disturbances involving loss of multiple lines and/or generators can lead to cascading failures in the whole system, often referred to as system voltage instability. The power system will be considered to be in a vulnerable state when it is facing a threat of widespread outage[5]. Cascading failures in power grid bring great inconvenience to people’s lives and are very harmful to both power industries and the social economy. To avoid such failures, various power system protection approaches are usually in place in power grid. These protection procedures are executed to isolate the faults from an interconnected power network and to take control actions to restore supply to as much loads as possible. These protection procedures are normally associated with individual lines or generators, but there is usually no system-wide protection against system voltage stability.

Unlike other causes of breakdown, the first post-disturbance phase of system voltage instability presents a deceptively calm of a minute or more until conditions swiftly deteriorate during the disruptive second phase in the form of cascading failures[6]. It is therefore vital for the control nodes in the power grid to make fast and accurate decision during the first phase of post-disturbance. Control nodes in this case refer to generator controllers, on-load...
load changing transformers and circuit breakers.

Agent technology, as a powerful artificial intelligence technique, has been used in power systems for different purposes. An intelligent agent is able to make rational decisions autonomously in a dynamic environment, namely blending pro-activity and reactivity, showing rational commitments to decision making, and exhibiting flexibility when facing an uncertain and changing environment\cite{7}. A multi-agent system is composed of several intelligent agents, and individual agents may perform different roles. The agents in a multi-agent system can work autonomously, make decisions independently and interact with each other to achieve global goals.

Most of the existing multi-agent-based power grid management systems have central controllers which administer various activities of the systems. However, it is difficult for these systems to execute system-wide sequential actions in large interconnected power systems, which include communication, analysis, prediction and decision making, within a short time.

To overcome this limitation, decentralised multi-agent systems for power grid management have been proposed\cite{3}, which allow nodes in the systems to communicate only with their neighbours to acquire relevant information to make local decisions. The information obtained by using this approach may be incomplete since only information from the neighbouring nodes is available which may lead to sub-optimal solutions.

In this paper, a hybrid multi-agent framework is proposed for fast power system restoration in its first post-disturbance phase, thereby avoiding cascading failures.

The paper contributes in the following two aspects: (1) the proposed hybrid framework combines the benefits of both centralised and decentralised architectures, thereby avoiding a single point of failure and providing sufficient information for the agents; (2) the framework is topology independent and, hence, suitable for any network configuration.

2. Agent and Multi-Agent System

Intelligent agent is a powerful artificial intelligence technology, which shows considerable promise as a new paradigm for power system control, because agents are designed to operate in distributed or complex environments.

In the last decade, intelligent agent technology has been adopted for various aspects of power systems management, such as restoration\cite{2}, relaying\cite{8}, maintenance\cite{9}, substation automation\cite{10}, and state estimation\cite{11}. This paper focuses on self-healing smart grid system when one or several generators in the grid are out of order.

A multi-agent system (MAS) is a collection of agent systems in which two or more agents interact or work together to perform a set of tasks, or to satisfy a set of goals\cite{12}.

Jung and Liu\cite{5} presented a multi-agent framework that provides real-time information acquisition and interpretation, quick vulnerability evaluation of both power and communication systems, and preventive and corrective self-healing strategies to avoid catastrophic failures of a power system. However, their framework is only a preliminary work, and many details still need to be done.

Nagata and Sasaki\cite{13} developed a multi-agent framework for power system restoration. Their framework is in centralized design, which consists of several bus agents and a single facilitator agent. Bus agents are used to decide suboptimal target configuration after a fault occurrence, while the facilitator agent acts as a manager in the decision process. Nagata et al.\cite{14} improved the restoration methodology proposed in\cite{13}. But facilitator agents are still required for coordination of the agents. Momoh and Diouf\cite{15} refined the work done in\cite{14}. They utilized power generation agents, bus agents, and circuit breaker agents to distribute the reconfiguration functionalities. However, the system proposed in\cite{15} still needs facilitator agents. The methods proposed in\cite{13},\cite{14}, and\cite{15} are centralized multi-agent systems. The centralized manner may be too slow to respond to emergency situation associated with catastrophic disturbances.

To overcome the drawback of centralized methods, some decentralized multi-agent systems have also been presented. In\cite{11}, Nordman and Lehtonen proposed a new agent concept for managing an electrical distribution network. Their concept consists of three aspects, which include secondary substation object, decentralized functionality and an information access model. However, because all secondary substations are copies of the secondary substation objects, all secondary substations are homogeneous with the same type of agent intelligence. This homogeneous feature might limit the adaptation of this concept. Moreover, according to their decentralized functionality, when a primary substation wants to deliver a permission message to a specific secondary substation, the primary substation has to pass the permission message along the communication path instead of directly to the target secondary substation. This communication feature might incur communication costs, and cause delay in the decision making during emergency situations.

Solanki et al.\cite{15} provided a multi-agent framework with detailed design of each agent, which is used to restore a power system after a fault. The framework is decentralized and topology independent which can overcome the scalability of limitations of existing restoration techniques. However, the decision accuracy usually cannot be guaranteed. This is because each node in the decentralized
architecture only has a limited view of the whole working environment and makes decisions based only on its incomplete information. Moreover, their work overlooks negotiation process of the multi-agent system, which is very important for a multi-agent system to perform properly.

In this research, a hybrid multi-agent framework (HMAF) is proposed for self-healing smart grid systems, which deploy intelligent agents in different power grids, e.g. buses, generators and transformers, to execute monitoring, analysing, and maintaining activities. Agents in different nodes can also interact with each other to exchange their local information and decisions. Through binding intelligent agents to power grids, we can decompose and allocate complex problems to local agents. In this case, a power grid system can be considered as a MAS, and many agent coordination techniques could be borrowed to solve load balancing and system protection problems in the power system domain. It is a decentralized method, but in contrast to current decentralized approaches[11][15], our framework can provide sufficient information for nodes to make accurate decisions.

3. Design Consideration

An agent can be defined as an intelligent entity, which performs given tasks by using its knowledge and information gleaned from the working environment. It can act in a suitable manner toward achieving the given tasks successfully based on the following common properties[16][17], particularly in power grid systems:

- **Autonomy.** An agent has some level of self-control ability. It can exist and execute tasks in an environment without external directions. In power grid systems, it is necessary for each node to make decisions autonomously in order to achieve quick response when there are some faults occurring. In addition, autonomy could take the pressure off system operators who form the last line of defence.
- **Adaptivity.** An agent has the ability to learn and improve its performance with previous experience. In power grid systems, a node should be able to make precise decisions based on its previous experience and current states.
- **Reactivity.** An agent can perceive its environment and respond in a timely fashion to changes that occur in the environment. In power grid systems, a node should have the ability to perceive the change of its environment and act in real time in order to reduce the loss when a fault happens.
- **Sociality.** An agent has the ability to interact, communicate and work with other agents. When a fault occurs in a power grid system, it might be inevitable for some nodes to cooperate together to deal with the fault.

Therefore, the nodes in the power grid system should be able to communicate and negotiate with each other. In order to realize our framework, we choose belief-desire-intention (BDI) agent architecture for the framework design. The main reason to use BDI agent architecture is that a BDI agent[18] is able to continuously reason about beliefs, goals and intentions, and acts accordingly. There are four major concepts in the BDI architecture:

- **Beliefs** of an agent are information about the environment. Beliefs can also include inference rules, allowing forward chaining to lead to new beliefs.
- **Desires** are goals assigned to the agent. They represent objectives or situations that the agent would like to accomplish or bring about.
- **Intentions** are commitments by an agent to achieve particular goals. Intentions represent the deliberate state of the agent: what the agent has chosen to do.
- **Plans** are sequences of actions that an agent can perform to achieve one or more of its intentions.

4. Hybrid Architecture

To satisfy the requirements of smart grid systems, we propose a framework which deploys a layered architecture, i.e., the scheduler layer and the coordination layer, to ensure accurate and quick response. In each layer of the system, a number of intelligent agents are used to monitor and manage loads in different nodes.

Fig. 1 shows the architecture of the framework. From Fig. 1, it can be seen that the power grid system is divided into a number of small grids, and the dashed arrows demonstrate the communication directions between different agents. A local scheduler agent (LSA) is assigned to each grid to monitor and manage loads within the grid. To facilitate each LSA making accurate decisions, we allow interactions among different LSAs. Namely, different LSAs can exchange their local information in order to make more accurate decisions. In addition, the framework includes a local coordinator agent (LCA) in each area to coordinate the corporation of different LSAs, and the LCA has a global view of its associated area. Similarly, above the LCA, there is a higher level coordinator agent (HLCA) that coordinates the corporation of different local coordinator agents (LCAs). The functionalities of LCA and HLCA are the same. This paper concentrates on the interactions between LSAs and LCA, since the interactions between LCAs and HLCA are analogous as those between LSAs and LCA. Thus, it can be found that there are two types of relations in HMAF. One is “peer-peer” relation which exists between LSA-LSA and LCA-LCA. The other is “superior-subordinate” relation which exists between LCA-LSA and HLCA-LCA. Therefore, HMAF, which is benefited from hybrid architecture, can adapt to any scale of power grid systems.
5. Operations of HMAF

To demonstrate the operation of HMAF, an example is introduced in Fig. 2, where Gen 1, 2, 3 and 4 denote Generator 1, 2, 3 and 4, respectively, and the arrows indicate loads. As displayed in Fig. 2, Local View 1 consists of Generator 1 and Load 1, 2 and 4; Local View 2 is composed of Generator 2, Load 2 and Load 5; Local View 3 is formed with Generator 3, Load 7 and Load 8; Local View 4 contains Generator 4, Load 6 and Load 9. Based on HMAF, the power grid system shown in Fig. 2 can be mapped into a multi-agent framework which is displayed in Fig. 3. It is assumed that there is a fault on Generator 1 and the local scheduler agent 1 (LSA 1) has detected this fault. Then, the LSA 1 will attempt to request other LSAs for help to restore its local power.

As in Fig. 1, the dashed arrows in Fig. 3 indicate the communication links, while the solid arrows in Fig. 3 denote the power flow directions. The current load and capacity of each generator are listed in Table 1.

LSA 1 first requests its neighbours for help with conversation ID “Request” and the request content is “Need Power: 60 kW” (60 kW = Load 1 + Load 2 + Load 4).

<table>
<thead>
<tr>
<th>Generator</th>
<th>Current load (kW)</th>
<th>Capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load 1=30, Load 2=20, Load 4=10</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>Load 3=25, Load 5=30</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>Load 7=15, Load 8=20</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>Load 6=5, Load 9=35</td>
<td>60</td>
</tr>
</tbody>
</table>
The neighbours of LSA 1 are LSA 2 and LSA 3, which reply LSA 1 with conversation ID “Response” and the response content is “Available Power: 15 kW” (Available Power = Capacity – Current Load) of LSA 2 and “Available Power: 25 kW” of LSA 3. LSA 1, then, sends two request messages with conversation ID “Request” and content “Power Supply Request: 15 kW” and “Power Supply Request: 25 kW” to LSA 2 and LSA 3 separately. Then, LSA 2 controls Generator 2 to supply 15 kW to the area which is supplied by Generator 1, and LSA 1 arranges this power to Load 1 that is supposed to be vital load in Local View 1. Meanwhile, LSA 3 designates Generator 3 to supply power 25 kW to Generator 1 area, and, similarly, LSA 1 allocates this power to both Load 1 and Load 4 (Load 1 gets 15 kW while Load 4 obtains 10kW). Since the current load of Generator 1 is 60 kW which is higher than the power Generator 2 and Generator 3 could supply, LSA 1 will ask Local Coordinator Agent 1 (LCA 1) for more information in the system. LSA 1 sends a “MoreNode” message to LCA 1. LCA 1 then responds a message with conversation ID “NodeInfo”, while the content includes the AgentIDs of other nodes in the system and their current load and capacity. When LSA 1 receives this message, it reasons which agents can supply its power. In this example, the reasoning result is that Generator 4 can supply the power 20 kW. Thereby, LSA 1 sends a request message to the selected agent, namely LSA 4 in this example, according to its AgentID with the conversation ID “Request” and content “Power Supply Request: 20kW”. As long as LSA 4 receives the request messages, it supplies the designated power to the area which was supplied by Generator 1, and LSA 1 assigns this power to Load 2. The interaction process is displayed in Fig. 4. In this example, Generators 2, 3 and 4 can supply sufficient power for Generator 1. However, in some cases, if other generators could not provide enough power for Generator 1, Generator 1 would have to make a decision about discarding current load, and asks LCA to estimate whether this decision is reasonable and to advise the LSA for more optimised solution.

6. Conclusions

In this paper, a hybrid multi-agent framework for self-healing smart grid system has been proposed. The contribution of this framework is that it combines centralized and decentralized architecture together. In contrast to centralized controller, this framework will allow faster response during emergency control associated with catastrophic disturbances. In contrast to complete decentralized architectures, central controllers are advised of the decision of local controllers and are asked to judge the decision and asked to suggest more optimized solution.

References

Darmawan Sutanto received the B.Eng. (Hons.) and Ph.D. degrees from the University of Western Australia, in 1978 and 1981 respectively, both in electrical engineering. He joined the School of Electrical Engineering at the University of New South Wales in 1982 and the Hong Kong Polytechnic University as a professor in Electrical Engineering in 1996. Since 2006, he has been with the School of Electrical, Computer and Telecommunications Engineering at the University of Wollongong as the professor of power engineering. His research interests include energy storage systems, voltage stability, harmonics and power electronics applications in power systems.

Dr. Sutanto is a senior member of IEEE. He was appointed as the Regional Representative of the Power Engineering Society of IEEE for Region 10, Asia-Pacific from 2001-2004. He has been invited to be the members of international advisory board for several international conferences. Now he serves as the General Chair of 2011 IEEE International Conference on Smart Grid and Clean Energy Technologies (IEEE ICSGCE 2011).

Da-Yong Ye is currently pursuing the Ph.D. degree with the University of Wollongong. His research interests focus on multi-agent systems, self-organized systems, task allocation protocols in distributed systems and agent-based modeling in complex domains.

Min-Jie Zhang is an associate professor with the School of Computer Science and Software Engineering and the Director of Intelligent System Research Group in the Faculty of Informatics at University of Wollongong, Australia. Her research interests include multi-agent systems, agent-based simulation and modeling in complex domains, agent-based grid computing, and knowledge discovery and data mining.