Distributed Multi-Agent Microgrids: A Decentralized Approach to Resilient Power System Self-healing

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Abstract—**The predominance of recent self-healing power system research has been directed towards centralized command and control functions. In this paper, a decentralized multi-agent control method for distributed microgrids is introduced. Given the complexity of a large power system spanning hundreds of miles and comprised of numerous microgrids, it is potentially unrealistic to expect that centralizing total system control functions is feasible. Therefore, the authors are particularly interested in dispersing decision-making by utilizing smart microgrid control agents that cooperate during normal and emergency situations. The combination of microgrids and agent-based control can improve power system resiliency. The method described herein lays the groundwork for a comprehensive microgrid control architecture that strikes a balance between the multiple intra-microgrid objectives defined by local operator and the situational demands of the microgrid collective as part of the power system. In this way, both self-interest and cooperation can arise, allowing microgrid agents to successfully transition from normal operations to an emergency condition and back again when conditions have resolved, independent of a central supervisor. The decentralized multi-agent methods for microgrids explored in this paper help to support what may be an enabling technology of future smart grids.**

Index Terms–**Microgrids, Multi-agent, Resilience, Self-healing.**

I. INTRODUCTION

Despite making progress, there remains great uncertainty about how smart grid technologies will emerge and ultimately influence the future electrical infrastructure. Complicating continued expansion of utility network capacity is the nearly 40% predicted growth of consumption demand over the next 20 years [1]. As demand continues to rise, increased pressure will be placed on existing conventional central power plants, transmission assets, and distribution systems. One technology that offers solutions for power system expansion and addresses smart grid objectives is microgrids. Although there is little consensus on a standard definition, for the purpose of this paper, 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. Microgrids are particularly attractive when seen as autonomous self-contained power system components. Assets connected within the microgrid, especially intermittent renewable sources, can be coordinated and controlled in a decentralized way. This allows diverse distributed energy resources (DER) to provide their full benefits while reducing the coordination and control burden on the utility grid [2]. From a control perspective, the primary goal of microgrids is to significantly improve energy delivery to local customers, while facilitating a more stable electrical infrastructure and benefitting environmental emissions, energy conservation, and operational cost. Microgrids offer utility networks a means to achieve higher DER penetration without the burden of its management; microgrids take responsibility for local asset control thereby adding flexibility to the entire power system.

The primary focus of this paper is to report on recent research directed towards employing a distributed multi-agent system (MAS) architecture to achieve resilient self-healing power systems through independent management of microgrids. The general approach expands on concepts, similar to those described in [3] for shipboard applications, of centralized MAS operations for self-healing power systems. However, the research in this paper is fundamentally different; rather than rely on hierarchical centralized supervisory control, a decentralized management and control scheme for distributed microgrids is proposed. Using a similarly decentralized MAS to that shown in [4], the approach in this paper uses agent cooperation through negotiation and the resulting MAS self-ordering to achieve system transitions from emergency to stable conditions. The paper is laid out as follows: Section II reviews recent self-healing research and highlights commonalities. In Section III, the concept of MAS and application to microgrids at the utility grid level is introduced. An overview of a MAS is developed to examine distributed decision-making towards power system operation and reconfiguration is shown in Section IV. The microgrid MAS is simulated in Section V showing a dynamic self-healing scenario and conclusions are given in Section VI.

II. SELF-HEALING

Simply, self-healing is defined as the capability for a system to automatically detect and recover functionality when faced with a single or many casualty events. For a power system, this definition is somewhat refined to include the rapid identification of problems, actions to minimize any adverse impacts from casualties, and the prompt recovery of the system to a stable operating state, if possible [5, 6]. Although sometimes not defined, there are two distinct periods for self-healing: first, the emergency reaction stage, followed by the restorative stage. During the first stage, a casualty condition is detected and the system reacts to minimize it, typically through isolation. Many emergency reactions may be automatic or predetermined, but have the effect of placing the system in a safer, less perilous condition. Once the system has

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transitioned beyond the initial emergency, restoration can begin. During restoration, a series of reconfigurations may take place improving overall system condition, involving breaker manipulations, generation startup or shutdown, load shedding or pickup, or other actions that change system operational posture. The restoration stage may be both a longer and more complicated self-healing stage, requiring more complex decisions. Typical performance measures of self-healing may include the speed a stable configuration is reached, the quantity of components that remain energized, and the minimization of equipment cycling during restoration.

Within the past decade and a half, the notion of resilient and self-healing power systems has become more prominent. Much of the self-healing literature and research within the power systems field is influenced by [7] and later additions, including [8] and [9]. In [7-9], a broad description of a comprehensive, multi-layered self-healing power system infrastructure is given. Subsequent literature has clarified and added to this initial vision, but a fundamental reliance on a strong centralized supervisory controller that encompasses global system awareness, in-depth pre-contingency analysis, and/or complex predictive planning cycles remains. Very little attention has been paid to truly decentralized and distributed decision-making that can accomplish similar self-healing objectives. While the reasons for this are unclear, two factors appear to have influenced the recent research direction. First, conglomerating communication, sensory, and control functions in a central manner allows decisions to be made with a global perspective. While it is cumbersome to centralize these functions, this facilitates the most complete information for decision-making. The second factor that may have discouraged development of capable distributed multi-agent systems is their difficulty. Without a dominant central supervisory force, achieving prioritization and cooperation for distributed control is a primary challenge. However, decentralizing decision-making has unique attributes that make it attractive from a resiliency perspective; chiefly because it can avoid the scenario where corruption or failure of the central supervisory node leads to total system collapse.

An example of a proposed multi-layered hierarchical system is given in [10]. Conceptually similar to [7], lower level agents perform reactive functions, while middle and higher level agents perform more complex forecasting and strategic functions. Clearly, architectures of this type have the potential to achieve self-healing objectives at the cost of significant computational, communication, and sensory complexity. Proposed self-healing schemes such as in [10] and [11] rely on large data flows of real-time power system monitoring information and predetermined network topologies to determine how to reconfigure the power system. In [12], the authors review the challenges that conventional power system protection and control technology pose to self-healing objectives, but similarly propose a centrally-based architecture dependent upon significant amounts of system data to formulate global state estimations. These computationally intensive predictions of system-wide health guide reconfiguration decisions, but the authors of [12] acknowledge that centralizing system monitoring and decision-making is cumbersome, requiring surmounting numerous technical gaps. A key point made in [13] for centralized real-time decision-making is that courses of action based on predefined models of an unpredictable environment can have detrimental effects on system behavior. In the method described in [13], when confronted with an power system emergency, network islands are formed first and subsequently load is shed within the islands to achieve stability. This method requires that islanding decisions be pre-scripted or determined in situ by a central supervisor with global knowledge.

A bottom-up approach utilizing intelligent switching components for a power system in a fault-prone area is described in [14]. Using dedicated VHF links for peer-to-peer communication, distributed controllers have responsibility for individual feeders with multiple reclosers and breakers to isolate areas of a power system during emergency situations. Primarily, [14] shows how effective delegating emergency reaction responsibility to a lower hierarchical level, closer to the affected area, can be as a self-healing method. This is an example of retaining self-healing capability without the need for centrally-dictated actions. Relatedly, in a move towards a diversified MAS, [15] outlines a complex hierarchy with both a central supervisory agent and many distributed agents that handle automatic emergency reactions. Different, however, from [14] and having intense reliance on information flows, the multiple control layers described by [15] depend on fast simulation and modeling to estimate future states, anticipate problems, and make system self-healing decisions.

Shipboard power system research has yielded interesting results for the self-healing question, but has commonality with methods described above. For example, in [16], the shipboard power system is modeled as a graph (edges and nodes) and formulated as a fixed charge (cost) network flow problem; the objective being to find the optimal post-event configuration using priority-weighted loads to maximize total shipboard load, while satisfying constraints such as unavailable equipment. Most shipboard self-healing methods rely on global knowledge by a central supervisor and therefore are similar to conventional power system self-healing methods. Even proposed shipboard self-healing methods that suggest multi-agent applications, such as [3], utilize hierarchical control and rely on central supervisory functions.

Clearly, for a power system to be effective at self-healing, it must encompass some fundamental traits, including: the ability to interpret emergencies, react promptly to abnormal situations, and a decision-making framework that guides the system to safe operation. While the majority of effort has been focused on centralizing these capabilities, distributed MAS intelligence may offer an alternative for computational and system complexity required by previous methods.

III. MULTI-AGENT FRAMEWORK

MAS is defined as a collection of autonomous computational entities (agents), which can be effective in broad applications performing tasks based on goals in an environment that can be difficult to define analytically. Often within MAS architectures, autonomous agents work with a limited system-wide perspective and focus on localized task achievement [17]. Although each agent's ability to affect the system environment is limited to the capabilities of their immediately controllable system or component, agents can communicate information about their goal achievement to other independent agents comprising the MAS. Cooperation arises as agents propose, accept, reject, or counter-propose courses of action based on conferring with other agents, assessing local capabilities, and evaluating native objectives.

The Java Agent Development Framework (JADE) is a Foundation for Intelligent Physical Agents (FIPA) compliant package that implements standardized Agent Communication Language (ACL) for MAS systems [18]. JADE allows the development of unique software agents that can perform a myriad of tasks, control functions, and supports decentralized control architectures. Once initialized, the algorithmic "container" that facilitates agent interaction can be easily replicated for redundancy, improving the control system survivability. When operating, the microgrid MAS described in this paper is accessible for communication by other FIPA-compliant platforms, such as from the utility grid, neighboring microgrids, etc. The JADE-based agent platform directly supports "plug-and-play" connectivity, as agents come on- and off-line asynchronously.

Distributed multi-agent systems can be difficult to develop because of tradeoffs between strict definitions of autonomous behavior and the need for agents to interact. In this way, multi-agent system development is a struggle between agents acting in a self-interested way and in a cooperative manner. Potentially the most challenging aspect of a distributed MAS without a centralized supervisor is system organization and prioritization. In other words, at each instant, the agents that comprise the MAS must evaluate their local situation, determine what solution best achieves the agent's unique goals, communicate their intended action to the MAS, participate in any prioritization among the agents within the MAS, and adjust its action based on the decision of the collective group. For the self-healing problem at hand, agents assigned to manage generation and load within each microgrid do not have global knowledge of the entire power system. Therefore, protocols that promote interaction and cooperation between autonomous microgrid agents are focused on cooperatively balancing resources on the power system as a whole. When faced with emergency situations, such as the loss of a microgrid or a faulted line, agents autonomously sense and react to the imbalance for the purpose of reestablishing the system, as is explained in the next section.

IV. AGENT PROTOCOLS

The practice of decision-making is a very familiar process for humans. However, attempting to codify the decision-making process in a meaningful, efficient, and useful way is often very challenging. As a consequence, implementing effective autonomous decision-making for automated systems can be difficult. Additionally, implementation is complicated by the need to make judgments rapidly and to seek an ideal conclusion amongst a field of many options and factors. The microgrid power management MAS is an example of an automated decision-making framework that must comprehensively consider complex factors that affects a complex system. The collection of agents, each assigned responsibility for the generation and load dispatch of a unique microgrid, makes up the MAS that, as a group, addresses system reconfiguration inherent to the self-healing problem. All agent algorithms, described below, were developed in Java, utilizing the JADE package libraries.

A. Normal Operation

For the purpose of this paper, it was of primary importance to show the cooperative functions of the MAS; in other words, how a decentralized framework can achieve self-healing objectives that have heretofore been primarily addressed in a centralized manner. To simplify the discussion, the power system context for this MAS application was reduced to real power flows only. By no means a restriction, microgrid agent development is completely flexible, allowing the incorporation of other factors such as reactive power flows, voltage and frequency, synchronization concerns, economic factors, etc. Although decision-making domains have been limited for this demonstration, further functionality is readily implementable.

Under normal circumstances, agents operate under a primarily self-interested protocol. Within each microgrid, a certain quantity of generation capacity (kW) is installed. The agent is not concerned with the type of generation resource explicitly, but instead relies on information regarding the status of local generation assets. Likewise, the quantity of installed load at each microgrid is known. For the purpose of experimentation, 20% of each microgrid's installed load is designated as vital and the rest is non-vital. This is arbitrary and can be modified depending on simulation requirements. Agents continuously assess the following primary variables:

a. Instantaneous total generation capacity (kW)
b. Current generation operating level (kW)
c. Current load operating (kW)

The microgrid agent has the ability to ramp generation up or down based on the constraints of the generator and the available resources. Likewise, the microgrid agent can start or stop vital and non-vital loads based on the situation. The agent's prime objective is to maintain power to the vital loads within its microgrid at all times. If locally available power cannot sustain vital loads, then the agent will communicate to other agents seeking assistance. Clearly, this objective could be obviated if adequate dispatchable generation were mandated to be implemented at each microgrid, but this is not necessarily realistic. Under normal operations, if available generation capacity exceeds that which is required to power vital loads locally, then either non-vital loads are switched on incrementally or power is exported to neighboring microgrids who have requested it. The microgrid agent operates local generation and load based on the following priority hierarchy that incorporates both self-interest and cooperation:

1. Local microgrid vital load requirements.
2. Neighboring microgrid emergency vital load requirements.
3. Local microgrid non-vital load requirements.
4. Neighboring microgrid non-vital load requirements.

In this way, the microgrid agent seeks to energize the maximum number of local vital and non-vital loads based on local generation. If local generation is adequate to meet vital load requirements, but not to fully energize non-vital requirements, the microgrid can transmit a surplus request to other microgrids for assistance. Based on the priority hierarchy, a microgrid that receives the surplus request and has generation capacity in excess of its own vital and non-vital load requirements can export power to the another microgrid.

As will be shown in Section V, the microgrid agents interact as to utilize the maximum quantity of available generation possible. This is considered a maximum power utilization strategy. Specifically, each microgrid agent continuously attempts to fully energize local loads and, if conditions permit having accomplished this, will seek to export any excess power to other microgrids. In this way, microgrid agents are discouraged from curtailing generation if resources are available. This simulates the maximum utilization of available renewable sources, such as wind and photovoltaics, which are inherently intermittent, but desirable to operate maximally when available. In cases where the generation mix across microgrids includes both dispatchable and renewable sources, additional objectives come into play which compels modifying the maximum power utilization strategy, most commonly to account for costs. Clearly, the incremental generation cost for a unique microgrid, as well as the spot market clearing price, influences the normal operation priority hierarchy described above. However, for the purpose of this paper, demonstrating the cooperative effects of the multi-agent system were paramount and cost was neglected. Depending on desired complexity, the agent priority hierarchy can be modified to incorporate cost functions that account for changing costs and are fully integratable in the microgrid multi-agent framework.

Load prioritization across the power system is not considered in this formulation. In other words, from the microgrid agent perspective, all non-vital loads of neighboring microgrids are equivalent. When a microgrid has excess power available, it broadcasts this fact to all agents. If a microgrid agent determines that it desires the surplus power, it responds to the sender. Responses to these broadcasts are handled on a “first come, first serve” assignment basis. For example, if microgrid A has an excess of 100 kW and microgrid B is first to submit a non-emergency request for 80 kW of the surplus, then 80kW is designated for microgrid B usage. Subsequently, microgrid A reissues a broadcast for the remaining 20kW. When negotiations between microgrids are finalized, a temporary contract is formed between supplier and receiver microgrids for a quantity of power. This contract can be modified at any time as conditions change. As instantaneous power generated or load demand changes, the contracted parties attempt to incorporate the changes into their existing contract, but if unable, the contract is released and the system-wide negotiation process repeats for supply to match demand. A common example of this occurs when microgrid A, who is generating excess power for microgrid B, experiences a curtailment of excess power. When this happens, the microgrid A informs the microgrid B that it can no longer supply at the previous quantity. Microgrid B decides whether to curtail its load demand to match the new excess power quantity or terminate the contract.

The multi-agent framework readily facilitates new microgrids joining the power system. As a new microgrid becomes operational, it communicates its presence, establishes connections with neighboring microgrids, and transitions immediately into normal cooperative behaviors as a participant in MAS decision-making.

B. Emergency Operation

An emergency situation is defined as either a failure of a microgrid resulting in its loss from the system or a faulted transmission line that results in the loss of that power flow path from the system. Following an emergency event, the remaining microgrids must respond with actions to restore the system to the maximum extent possible. Microgrid agent behavior upon a casualty event is characterized first by an emergency reaction stage, followed by the restorative stage. Once each microgrid has locally taken immediate reactive actions and placed itself in a safe condition, then a restorative stage can begin. The reaction stage is unique to emergencies; the restorative stage is very similar to normal operation.

The reaction stage is initiated by the microgrid that sends an emergency MAS message upon first sensing a fault or a neighboring microgrid failure. Upon receipt of that broadcast, microgrids make emergency reactions to stabilize system power flow. This is done according to the algorithm, shown in Fig. 1, the primary objective of which is for each microgrid to transition to a self-sustaining state, therefore minimizing the transfer of power on the compromised power system. In this way, safe power system line connections are maintained and generation-to-load imbalances are minimized.

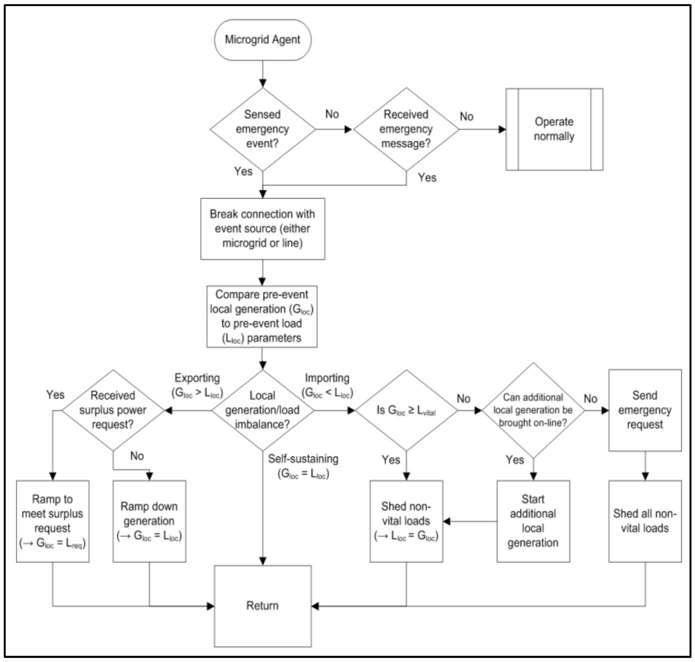

Fig. 1. Agent algorithm for actions under normal and emergency conditions.

At the outset, if a microgrid has broadcast an emergency message indicating that it cannot meet its local vital load requirements with local generation, then the multi-agent collective addresses this concern first. Each microgrid with available generation capacity in excess of its vital load requirements communicates its excess capacity and current list of available safe connections to the microgrid in trouble. By sending these emergency responses, the microgrid agents are declaring that they will forego supplying their own non-vital loads in order to help a neighboring microgrid power their vital ones. The microgrid in trouble determines which microgrid it will temporarily contract with for excess power based on the first positive response it receives.

Immediately following the emergency event and the completion of emergency reactions, it is very likely that some microgrids may have excess generation online. This is the beginning of the restorative stage. Microgrids that have shed non-vital load in the emergency transition transmit surplus requests, similar to normal operation, seeking additional power. During negotiation, the microgrids with excess generation pair with those that have shed load during the emergency. If the microgrids that enter into a temporary contract are connected by a transmission line that is safe, but not energized, they may determine to activate that line rather than wheeling power. Although beyond the scope of this discussion, performance measures, such as the percentage of microgrid loads energized, can be used by the MAS for prioritization when negotiating temporary power contracts.

As the restorative stage winds down, the multi-agent collective is ready to restore operations to the maximum extent possible, considering the new system topology. The multi-agent system transitions to a normal operating condition, except that some microgrid nodes and connections are now unavailable to the system. Likewise, the newly reconfigured power system operates according to the normal cooperative protocols, described in Section II-A above. The only exception is that, periodically, the microgrids that are nearest the faulted line or failed microgrid check to see whether the emergency condition has been rectified. If the emergency condition has cleared, the microgrids attempt to reestablish any prior connections with failed microgrids and incorporate them into normal operations.

V. SIMULATION EXAMPLE

For the purpose of demonstration, a small power system incorporating eight microgrids is simulated. The small power system experiences a fault scenario that causes the complete loss of a system microgrid, designated C4. As a result, the remaining microgrids must react and recover operations to the maximum extent possible. Table I annotates the initial operating conditions for the microgrids in the power system. The simulations were conducted utilizing custom interfaces with Java (Runtime Environment 6.24) and the JADE platform package. Upon initialization, when a microgrid agent joins the MAS, transmission lines that interconnect it to other microgrids and whether those lines are active/ inactive are assigned randomly for simulation. The microgrids and transmission lines for this power system simulation are shown in the geographic topology in Fig. 2. It is noted that, in this simulation, voltage and frequency transients are neglected, as are market economics and other objectives. This example is meant to highlight cooperative actions that microgrid agents initiate to restore the system to a semi-normal operating state following an emergency. There are no transmission constraints, so power can be wheeled without penalty.

In Fig. 2, each microgrid is represented by two conjoined circles; the leftmost represents generation and the rightmost shows load. The relative size of each circle represents either the total installed generation capacity or the total installed load, respectively. Throughout operations, the proportion of instantaneous generation, in kW, and load consumption, in kW, is shown as the colored portion within each of the two microgrid circles, similar to a pie chart. Transmission lines interconnect the microgrids; dashed lines represent inactive transmission lines, i.e. the tie breakers are open, and the solid lines represent lines that are active.

TABLE I: PARAMETERS FOR SMALL POWER SYSTEM

Microgrid Designator	Total Installed Generation Capacity (kW)	Total Installed Vital Load (kW)	Total Installed Non-Vital Load (kW)	Microgrid Load-to-Generation Ratio
C1	620	140	560	0.90
C2	400	60	240	0.60
C3	750	200	800	1.07
C4	680	70	280	0.41
C5	700	150	600	0.86
C6	450	60	240	0.53
C7	1000	210	840	0.84
C8	400	110	440	1.10
Total:	5,000 kW	1,000 kW	4,000 kW	

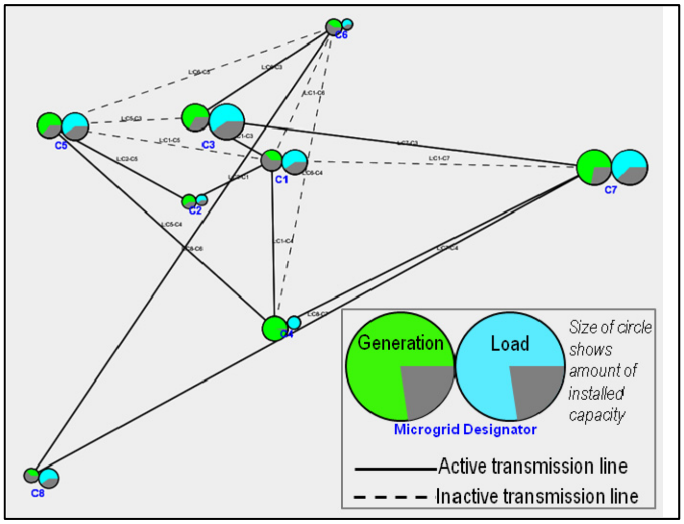

Fig. 2. Geographical depiction of simulated power system prior to emergency.

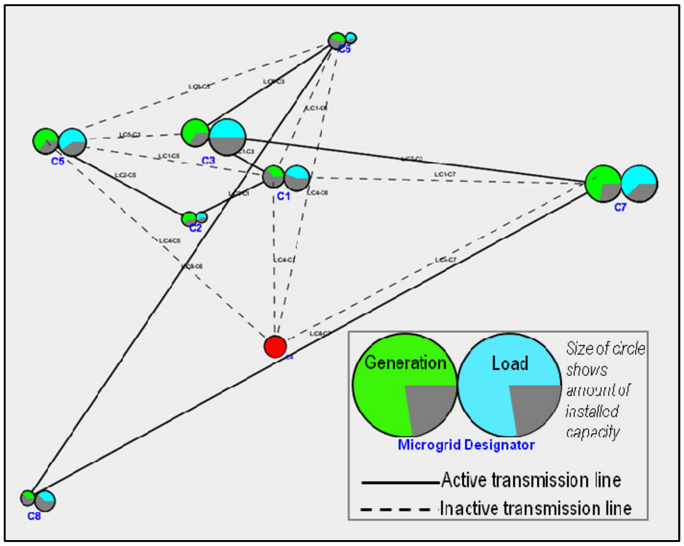

Fig. 3. Geographical depiction of simulated system in restored condition.

The initial conditions prior to the emergency event are annotated in Table II. Each microgrid is operating within individual limits and have been initialized to carry all of their native vital loads and 50% of their non-vital loads. Microgrids C2, C4, and C7 have excess power available that they are exporting to microgrids C1, C3, and C8. The emergency event is initiated by tripping the interconnection breaker for microgrid C4. As is shown by Table II, microgrid C4 was a significant contributor of surplus power to the power system. Its loss causes significant system disruption and is a catalyzing event for the system to self-heal. Immediately upon sensing the loss of C4, the MAS performs emergency reactions. Table III shows power system conditions upon completion of the emergency reaction stage (columns annotated as "ERS"); microgrids C1, C3, and C8 have reduced their operating non-vital loads to match their local generation; C2 and C7 with excess power available have transmitted surplus available messages to the MAS. Due to emergency reactions, the power system is in a stable transitory state as the restoration phase begins. Surplus available messages are processed by microgrids C1, C3, and C8 due to their load shedding actions and each responds to microgrids with excess power seeking temporary supply contracts initiated on a "first come, first served basis". Table III (columns annotated as "RS") shows the results of these restoration actions, where C2 supplies C8 and C7 supplies C1. The system has now self-healed itself to the maximum extent possible. Operations continue without the failed microgrid C4, shown geographically in Fig. 3.

TABLE II: PRE-FAULTED INITIAL CONDITIONS FOR SMALL POWER SYSTEM

Microgrid Designator	Instantaneous Operating Generation (kW)	% of Vital Loads Operating	% of Non-Vital Loads Operating	Import / Export Power (-kW in, +kW out)
C1	220	100%	50%	-200
C2	240	100%	50%	+60
C3	500	100%	50%	-100
C4†	680	100%	100%	+330
C5	450	100%	50%	0
C6	180	100%	50%	0
C7	720	100%	50%	+90
C8	150	100%	50%	-180
Total:	3140 kW	1000 kW	2140 kW	0 kW

†: Faulted microgrid results in total instantaneous generation of 2440 kW.

TABLE III: CONDITIONS FOR SMALL POWER SYSTEM IMMEDIATELY FOLLOWING EMERGENCY TO MICROGRID C4 AND AFTER RESTORATIVE STAGE

	% of Vital (ERS)	% of Vital (RS)	% of Non-Vital (ERS)	% of Non-Vital (RS)	Import/ Export Power (ERS)	Import/ Export Power (RS)
C1	100%	100%	14%	30%	0	-90
C2	100%	100%	50%	50%	+60	+60
C3	100%	100%	38%	38%	0	0
C4	0%	0%	0%	0%	0	0
C5	100%	100%	50%	50%	0	0
C6	100%	100%	50%	50%	0	0
C7	100%	100%	50%	50%	+90	+90
C8	100%	100%	9%	23%	0	-60
	930 kW	930 kW	1380 kW	1530 kW	150 kW surplus	0 kW

When the restorative stage has concluded, all system operation is as if the power network were in a normal state. As instantaneous generation or load fluctuates, the microgrids will respond and cooperate to meet their objectives in an identical manner to prior to the emergency, excluding the influence of microgrid C4. As such time that C4 is recovered, it rejoins the system under the normal protocol.

VI. CONCLUSION

Efforts to prepare for the energy future include measures to modernize electrical infrastructure towards better resiliency. That is, imbuing the ability to adapt and self-heal are important attributes of emerging smart grids. Microgrids are a logical choice to complement these goals, and managing them on a decentralized basis shows promise. In this paper, MAS framework has been discussed to facilitate self-healing for a power system that incorporates microgrids. A discussion regarding recent self-healing approaches has been made, as well as highlighting potential advantages for distributed control of microgrids. Agent protocols have been developed and a microgrid MAS simulation that demonstrates performance during a casualty requiring self-healing is shown. The power system self-healing and dynamic reconfiguration problem is difficult, but the case is made for combining multi-agent control and microgrids to this end.

REFERENCES

[1] Energy Information Administration-Office of Integrated Analysis and Forecasting, "Annual Energy Outlook 2011 – Early Release Overview", U.S. Department of Energy, DOE/EIA-0383ER, 2011.

[2] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power & Energy Magazine*, Vol. 5, Issue 4, July/August 2007.

[3] K. L. Butler-Purry, "Multi-Agent Technology for Self-Healing Shipboard Power Systems", *13th International Conference on Intelligent Systems Application to Power Systems*, 2005.

[4] K. Huang; S. Srivastava,, D. Cartes, "Decentralized Reconfiguration for Power Systems Using Multi Agent System", *Proceedings, 1st Annual IEEE Systems Conference*, 2007.

[5] M. Amin and B.F. Wollenberg, "Toward a smart grid: power delivery for the 21st century", *IEEE Power and Energy Magazine*, Vol. 3 , No. 5, pp. 34-41, 2005.

[6] K. Moslehi and R. Kumar, "Vision for a self-healing power grid", *ABB Review,* No. 4, 2006

[7] M. Amin, "Toward Self-Healing Energy Infrastructure Systems", *IEEE Computer Applications in Power*, Vol. 14, No. 1, pp. 20-28, 2001.

[8] M. Amin, "Toward a self-healing energy infrastructure", *IEEE Power Engineering Society General Meeting*, 2006.

[9] M. Amin, "Challenges in reliability, security, efficiency, and resilience of energy infrastructure: Toward smart self-healing electric power grid", *IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008.

[10] Z. Noorian, H. Hosseini, and M. Ulieru, "An Autonomous Agent-based Framework for Self-Healing Power Grid", *IEEE International Conference on Systems, Man, and Cybernetics*, 2009.

[11] P. Cox, "Self-Healing Networks Performance Improvement by Automated Switching Algorithm", *CIRED Seminar 2008: SmartGrids for Distribution*, 2008.

[12] F. Li, Z. Chen, L. Fan, P. Zhang, "Toward a self-healing protection and control system", *40th North American Power Symposium*, 2008.

[13] H. You, V. Vittal, and Z. Yang, "Self-Healing in Power Systems: An Approach Using Islanding and Rate of Frequency Decline-Based Load Shedding", *IEEE Transactions on Power Systems*, Vol. 18, No. 1, 2003.

[14] David MACLEMAN, Witold BIK, Andrew JONES, "Evaluation of a Self Healing Distribution Automation Scheme on the Isle Of Wight", *CIRED 20th International Conference on Electricity Distribution*, 2009.

[15] A. Valenti, I. Bel, and S. Lee, "High Level Requirements of Fast Simulation and Modelling Suite Of Tools for Future 'Self-Healing' Distribution Power System", *CIRED 18th International Conference on Electricity Distribution*, 2005.

[16] K. L. Butler-Purry, and N. D. R. Sarma, "Self-Healing Reconfiguration for Restoration of Naval Shipboard Power Systems", *IEEE Transactions on Power Systems*, Vol. 19, No. 2, 2004.

[17] G. Weiss. Multiagent Systems. Chaps 1-5, 11-13, MIT Press, Cambridge, MA, 1999.

[18] F. L. Bellifemine, G. Caire, D. Greenwood, Developing multi-agent systems with JADE. John Wiley & Sons, Hoboken, NJ, 2007.