

A Hierarchical Multi-agent Control Scheme for a Black Start-Capable Microgrid

Niannian Cai, *Student Member, IEEE*, Xufeng Xu, *Member, IEEE* and Joydeep Mitra, *Senior Member, IEEE*

Abstract—This paper presents a hierarchical control scheme using a multi-agent system for black start operation of a microgrid with power electronic interfaces. Five types of agents are proposed in this architecture, namely Grid Agent, Central Agent, Generation Agent, Load Agent and Breaker Agent. With this architecture, the multi-agent system is able to coordinate distributed generators (DG) and loads to maintain steady state operation of the microgrid either in grid-connected mode or islanded mode; it can also perform a black start if a seamless transition to the islanded mode fails or if a black start becomes necessary for any other reason. A system with four DG units is demonstrated using MATLAB/SIMULINK to demonstrate the operation of the proposed system.

Index Terms—Multi-agent system, microgrid, hierarchical control, black start, distributed generation.

I. INTRODUCTION

THE total electricity consumption in the US is predicted to grow from 3,873 billion kWh in 2008 to 5,021 billion kWh in 2035, at the rate of 1.0% annually [1]. Accompanying the increasing consumption, the percentage of renewable generation is expected to rise from 9% in 2008 to 17% in 2035. High penetration of renewable energy will introduce some new problems to conventional power system, such as energy management of renewable sources, frequency fluctuation, and distribution voltage variation. A promising way to manage these problems is to organize these renewable sources locally to construct an autonomous microgrid and connect it to the grid through a Point of Common Coupling (PCC) [2]. A microgrid can be defined as a tiny power system established by a cluster of interconnected distributed generators, loads, storage units and protection devices and be treated by the grid as a controllable load or source [3]. Microgrids benefits power industry by improving local reliability, providing voltage support, reducing feeder losses and increasing efficiency [4], [5].

A microgrid can be operated in two modes: grid-connected and islanded. In grid connected mode, microgrid is connected to utility and DGs can be controlled to produce rated real and reactive power to minimize power imported from the grid or be controlled to generate pre-specific real power and regulate its terminal voltage [6], and loads can consume at their demand levels due to the large capacity of the grid. Islanded mode usually happens when the main grid fails. In this operation, microgrid will detect the loss of the grid and disconnect

itself from the grid. To achieve stability in islanded control, microgrid should be operated to satisfy three requirements: power balance between total generation and consumption, voltage variation within a limited range, synchronization and frequency control among DGs [7].

Allowing microgrids to operate in islanded mode can reduce customer interruption time when the grid is unavailable. Microgrids are designed to have a high level of reliability with close monitoring and complex error correcting controls; however, microgrids may sometimes fail in severe situations. A failure in smooth transition from grid-connected mode to islanded mode or a disturbance occurring in islanded mode may bring about the outage of the microgrid. If medium voltage network does not restore in a short time, a local black start in microgrid is preferable to restore service. In conventional power systems, there are two types of black start: top-down restoration (energize high voltage grid first and then energize lower voltage systems) and bottom-up restoration (starting from individual generating units with black start ability and critical loads and synchronize them later) [8]–[10]. In a microgrid, due to its smaller number of units, shorter interconnects, diverse technologies and dispersed locations, the black start process has unique characteristics. References [11] and [12] identify a sequence of actions to restore microgrids and address the need of storage devices to guarantee system stability. In this paper, we propose a hierarchical architecture of multi-agent system to manage microgrid black start, in which autonomous agents have ability to detect loss of grid power, and execute a black start sequence.

This paper is structured as follows. In section II, a basic configuration of a microgrid is presented. Section III discusses a hierarchical architecture of multi-agent system and its function in normal operation and black start operation. Dynamic models for DG units are given in section IV and simulations to verify the effectiveness of multi-agent system in black start operation are shown in section V.

II. SYSTEM CONFIGURATION

A basic structure of microgrid considered in this paper is shown in Fig. 1. The microgrid system includes four distributed resources connected to the system with single phase inverters. Power ratings of these distributed generators are shown in Table I. DG1 and DG4 have an energy storage device in its DC link, which are not shown in this figure. These DGs are connecting to its local bus, where a centralized load is also attached. A point called PCC (point of common coupling) connects microgrid to medium voltage network.

This work was supported by the National Science Foundation under grant ECS-0702208.

The authors are with the Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI 48824, USA. (email: cainiann@msu.edu)

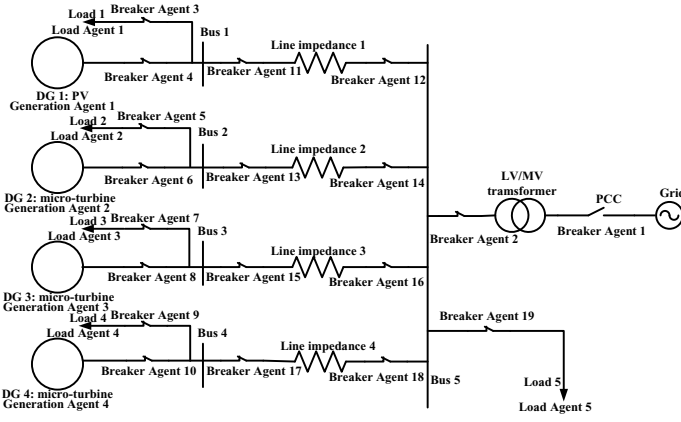


Fig. 1. Configuration of microgrid

Another centralized load 5 is connected to bus 5 through breaker 19. Voltage level for this microgrid is 120V. DG2, DG3, DG4 are black start capable and have both voltage control mode and real and reactive power control mode (PQ control) [13], while DG1 only has PQ control mode. DG4 with largest capacity and an energy storage device equipped, has a fast response and large tolerance to the disturbance happened in microgrid.

TABLE I
POWER RATING AND CONTROL MODES OF DGs

Units	Capacity (kVA)	Black start ability	Energy storage
DG1	$2 + j1.5$	no	yes
DG2	$2 + j1$	yes	no
DG3	$5 + j3$	yes	no
DG4	$10 + j5$	yes	yes

III. MULTI-AGENT SYSTEM

Multi-agent system is a system containing two or more autonomous entities that can detect and react to its environment and communicate with each other to optimize its local goal, and therefore system's global goal is obtained. The role of implementing multi-agent system is to break down a complicated control problem into several small simple problems, and each simple problem will be handled by an agent [14]. Agents have a certain degree of autonomy that it can make decisions based on the information it acquires from environment without a central controller [15]. Previously, some work has been done on multi-agent system. Ref. [16] reviews the fundamentals of multi-agent system and presents possible contributions that MAS can provide to power engineering. Ref. [17] gives instructions and advices on the design and implementation of multi-agent system. Ref. [18] discusses optimal control of multi-agent system to provide voltage support on a distribution feeder. Ref. [19] proposes a decentralized approach to isolate the fault and restore power supply.

A. Agent architecture and specification

As displayed in Fig. 2, the multi-agent system of the proposed scheme consists of five types of agents, namely Grid Agent, Central Agent, Generation Agent, Load Agent

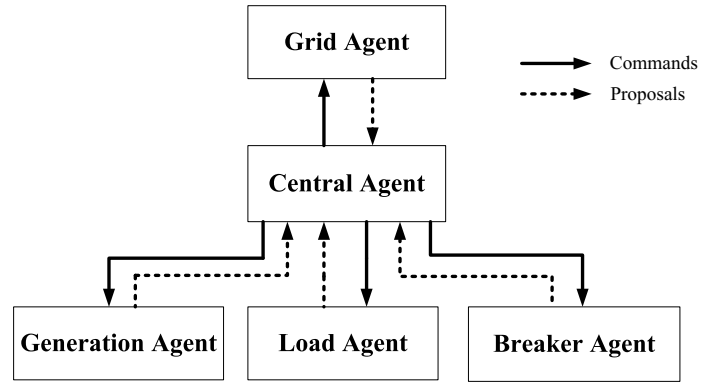


Fig. 2. Architecture of multi-agent system

and Breaker Agent. Each agent has its specific role in the multi-agent system:

Grid Agent: Grid Agent monitors voltage and frequency of the grid and acts like an ambassador representing the grid to communicate with Central Agent, which is the governor of microgrid. Grid Agent is capable of detecting failure of the grid and sends signals to inform Central Agent when it detects the grid's outage.

Central Agent: Central Agent is the core agent in multi-agent system and in charge of optimizing microgrid operation, which includes monitoring grid and microgrid in grid-connected mode, optimal dispatching loads and generations in islanded mode, and conducting microgrid's black start procedure after microgrid fails. Central Agent has a list of Generation Agents and Load Agents within microgrid; so it can inform them of the immediate status of the grid and control them directly.

Generation Agent: Generation Agent will monitor the operation of the distributed generators, update Central Agent with generation informations, including: generator type, power rating, storage level, control modes and black start capability etc. Generation Agent also receives commands from Central Agent and controls its distributed generator in conformity to the commands.

Load Agent: Load Agent observes electricity consumption at user's side, updates load demand and load significance weight to Central Agent and increases or sheds load under commands of Central Agent. In the black start procedure, Load Agent will increase its load gradually and selectively under instruction of Central Agent.

Breaker Agent: Breaker Agent is responsible to change the breaker status under the command of Central Agent. Breaker Agent should open the breaker at Point of Common Coupling to disconnect microgrid from medium voltage network when Central Agent is informed of the grid outage by Grid Agent and gives open command to Breaker Agent. In the black start procedure, Breaker Agent will close breakers collaboratively in the sequence that forms microgrid under commands of Central Agent.

B. Control strategies for grid-connected and islanded operation

In grid-connected mode, Grid Agent is in charge of monitoring the operation and status of the grid by measuring voltage and frequency of the grid. It is responsible to inform Central Agent of the grid outage when grid fails. Generation Agents will operate in grid-connected mode that control its corresponding distributed generator to generate predefined real and reactive power or produce specific real power and regulate its terminal voltage. Load Agents can observe voltage and frequency at the customers' side and feedback customers' information to Central Agent.

When grid breaks down, Grid Agent detects the outage and sends signal to Central Agent to inform the fact of the grid outage. Receiving the notification of the grid failure, Central Agent immediately sends open command to the Breaker Agent at point of common coupling to open the breaker separating microgrid from grid. Then Central Agent will switch to islanded control mode. It will ask load information from Load Agent and generation capacity information from Generation Agent. Based on this information, Central Agent will optimally dispatch loads and generations in some pre-defined rules. For example: when total load demand is larger than total generation capacity, Central Agent will send commands to Load Agent to cut off some less critical load based on the load significance weight. On the other hand, when total load demand is less than generation capacity, Central Agent may control some dispatchable generators to reduce their production. Central Agent will also consider the cost of generation in the dispatching process. For example: when there are both photovoltaic cells and micro-turbines in microgrid. Central Agent may not want photovoltaic cells to reduce their power output, because they are cheap and less polluted. Instead, it will inform those Generation Agents which are in charge of micro-turbines to reduce their power output. The key issue concerned by Central Agent in islanded mode is to cooperate with Generation Agents and Load Agents to keep power generated equals to power consumed at any time within microgrid, thus to maintain the small system stable. After assignments are determined by Central Agent for Generation Agents and Load Agents, Central Agent will send these commands back to corresponding agents. Generation Agents receive the assignments and follow the instructions of Central Agent to regulate their real and reactive power output; Meanwhile, Load Agents receive assignments and cut off loads depending on the load significance weight.

The flow chart for microgrid's islanded operation under multi-agent system is shown in Fig. 3.

C. Black start procedure

In conventional power systems, power restoration and black start are conducted by system operators manually based on the pre-specific sequences. However, in microgrid, because of its small size and large quantities emerging in the future, system operators are not expected to hire to carry out black start procedures. Multi-agent system appears to be an effective way to organize and restore microgrid in this situation. Power

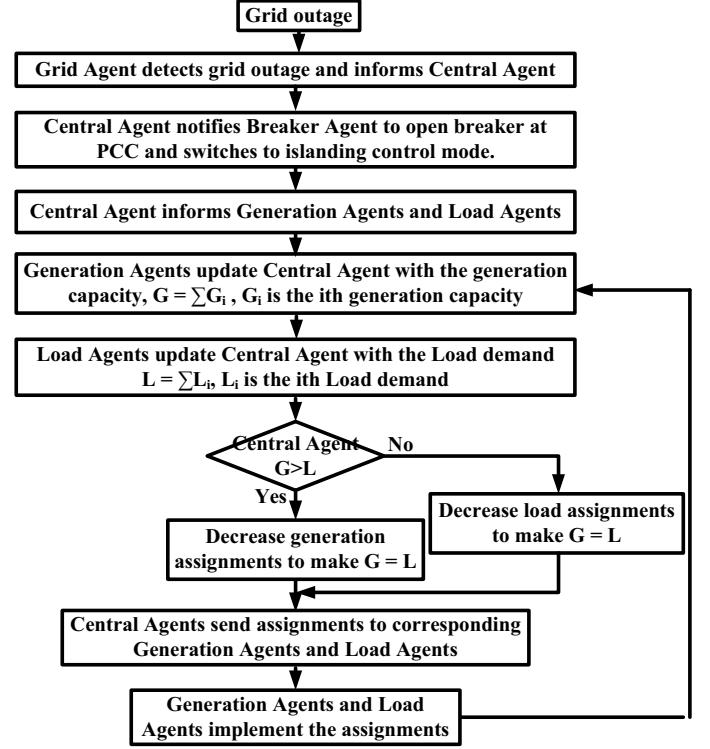


Fig. 3. Flow chart for microgrid islanded operation

restoration is much simpler in microgrid than in conventional power system, because of its less units; however, distinct characteristics, such as large integration of power electronic interfaces and fewer conventional generators, primary energy source response constants, require particular identification of restoration procedures for microgrid [20].

When microgrid fails to smoothly transit from grid-connected mode to islanded mode, or a large disturbance occurs in islanded mode causing microgrid breaking down, black start of microgrid is conducted by multi-agent system in the following specific steps and sequences for restoration:

- 1) Generation Agents renew corresponding distributed generators' information to Central Agent. The informations used for updating include: type of the generator, whether it is a conventional generator or a power electronic interfaced generation; capacity of the generator; generator's control mode and black start capability.
- 2) Load Agents update load demands and significance weights to Central Agent.
- 3) Central Agent selects a black start capable power electronic interfaced microsource with the largest capacity and an energy storage device connected to its dc-link or a conventional generator with largest capacity first. Send commands to corresponding Generation Agent to start it in voltage control mode with required voltage amplitude and unchanged voltage angle at its terminal; meanwhile, send commands to appropriate Breaker Agents to close breakers and Load Agents which are in the same feeder to increase appropriate amount of loads into microgrid. Voltage angle reference can be given as the same as

voltage angle of the grid when it fails. Energy conserved in the energy storage device or kinetic energy stored in the conventional generator can contribute to smooth transition when connecting to new sources and loads.

- 4) Central Agent selects another microsource with black start capability. Send commands to corresponding Generation Agent to run it in voltage control first and choose appropriate amount of loads near it to form another microgrid. Synchronize voltage phase with that of microgrid already established in step 1. When it is stable, connect these two microgrids, and switch the new added microsource's control mode to real and reactive control.
- 5) Repeat step 4 until all microsources with black start capability are connected to the microgrid.
- 6) Connect microsources that without black start capability to the microgrid one by one with proper amount of loads increasing at meantime.

The distributed generators' output and their corresponding proper loads selected in steps (3)-(6) are strictly subjected to the constraints in equation (1).

$$\begin{aligned}
 &\text{Maximize} && \sum w_i L_i \\
 &\text{Subject to} && S_{G_i}^{min} \leq S_{G_i} \leq S_{G_i}^{max} \\
 & && S_{ij} \leq S_{ij}^{max} \\
 & && \sum S_{G_i} = \sum S_{L_i} + S_{loss}
 \end{aligned} \tag{1}$$

where w_i and L_i are, respectively, the significance weight and demand of load i . S_{G_i} is the apparent power generation of distributed generator i . S_{ij} is apparent power flowing from bus i to bus j . S_{loss} is the total apparent power loss in the microgrid.

The proposed flow chart of the microgrid's black start conducted by multi-agent system is shown in Fig. 4.

IV. DYNAMIC MODELS FOR DGs

In this section, the dynamic models implemented to simulate a black-start microgrid are described. Models for distributed sources are built according to the models in [21]–[23]. As mentioned in section II, each distributed resource is connected to the microgrid through power electronic interfaces, which are controlled either in voltage control mode or in PQ control mode. For dc micro-sources, such as PV panels or fuel cells, power electronic interfaces can be single-stage DC/AC shown in Fig. 5(a) or double-stage DC/DC/AC shown in Fig. 5(b) [7]. For non-utility-grade ac, power electronic interfaces can be two-stage AC/DC/AC converter shown in Fig. 6(a) or multi-stage AC/DC/DC/AC converter shown in Fig. 6(b).

Control blocks for voltage control mode are shown in Fig. 7. The purpose of this control is to produce the desired output terminal voltage, which will be used to either set up voltage levels within the microgrid or help DG units smoothly connect to the existing microgrid. Controls are implemented in the dq reference frame so as to emulate the controls of three-phase power converters by creating a virtual Q axis as described in [24], [25].

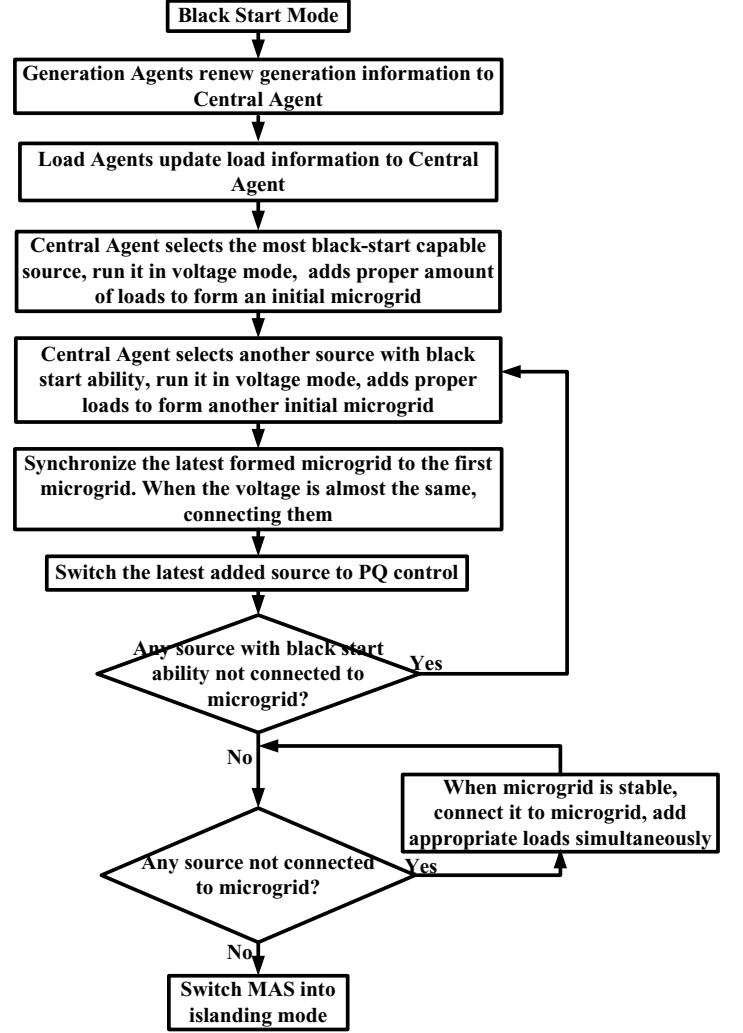


Fig. 4. Flow chart for microgrid black start

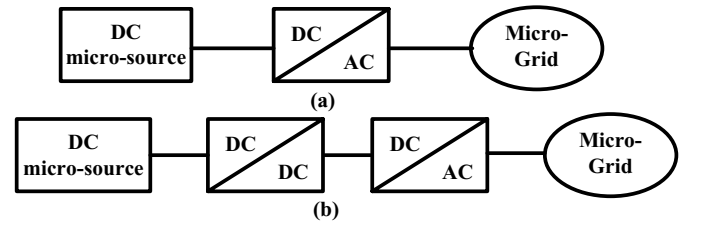


Fig. 5. (a) Single-stage power electronic interface for dc micro-source and (b) double-stage power electronic interface for dc-micro-source

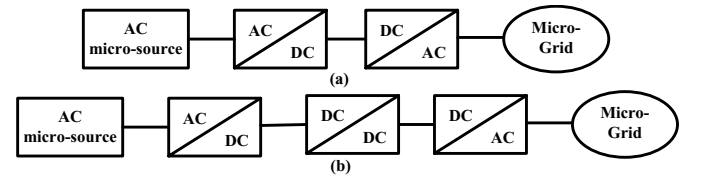


Fig. 6. (a) Double-stage power electronic interface for ac micro-source and (b) multi-stage power electronic interface for ac micro-source

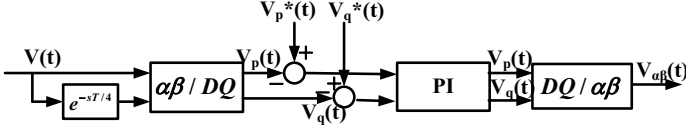


Fig. 7. Voltage control block for power electronic interface

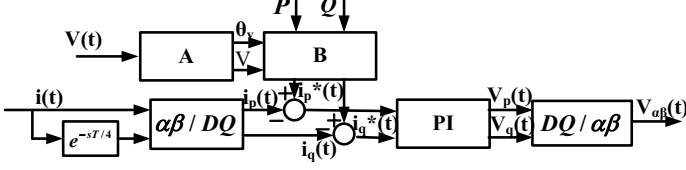


Fig. 8. PQ control block for power electronic interface

A PI controller is utilized to correct the error between the set-points and the real values measured at the sending point of power electronic interface. Products of PI controller will be inversely transformed to the stationary frame and treated as reference for the PWM generator for the switches in the bridge.

The PQ control block diagram implemented is shown in Fig. 8. The aim of this control is to provide specific real and reactive power into microgrid. Since voltage is certain and maintained by voltage sources, in order to output required real and reactive power from multi-agent system, DG units can adjust their current output to regulate power output.

The input of Block A is the voltage measured at the sending point of power electronic interface. It is operated as a low-pass filter and phase locked loop and produces the amplitude value V and phase θ_v of $V(t)$. P^* , Q^* are given from generation agents. Block B uses value of V , θ_v , P^* , Q^* to calculate instantaneous value of reference current $i_p^*(t)$, $i_q^*(t)$ by means of equations (2), (3):

$$i_p^*(t) = \text{Re} \left(\frac{P^* + jQ^*}{V \cos \theta_v + jV \sin \theta_v} \right) \quad (2)$$

$$i_q^*(t) = -\text{Im} \left(\frac{P^* + jQ^*}{V \cos \theta_v + jV \sin \theta_v} \right) \quad (3)$$

V. SIMULATION RESULT

In order to validate the performance of multi-agent system in conducting microgrid's black start, a system shown in Fig. 1 is simulated under MATLAB/Simulink environment to study the dynamic behaviour of microgrid. It was assumed that an outage has already happened in microgrid, distributed generators are all shut down, loads are shed and breakers are opened.

DG 4 is started at $t = 0$ s and selected as the first distributed generator to establish microgrid, since it has the largest capacity and a storage device connected to its DC link which could provide transient power for integrating new units. Breaker 9, 10, 17, 18, 19 are closed, so that Load 4 and Load 5 can be fed by DG 4.

At the same time, DG 2 and DG 3 are started in voltage control mode as DG4; however, they are running independently without connecting to DG4's microgrid with breaker

14, 16 open. Breakers 5, 6, 13 and 7, 8, 15 are closed; so that comparable local loads, Load 2 and Load 3, can be supplied by DG2 and DG3. At this time, there are three independent microgrids in the system with sources DG 2, DG3 and DG4 respectively. DG 1 has only real and reactive power control, so it is not black-start capable and cannot start in voltage mode at $t = 0$ s. After starting, DG 2 and DG 3 are trying to synchronize themselves with DG4's microgrid, which is the dominant microgrid in the system. At $t = 0.3$ s, when the DG4's microgrid is stable and DG3 has already synchronized with DG4, Central Agent sends signals to Breaker Agent 16 to close breaker 16 to connect DG4 and DG3. At $t = 0.41$ s, when DG2 has already synchronized with DG4 and DG3's microgrid, Central Agent sends signals to Breaker 14 to connect DG2 to DG4 and DG 3's microgrid.

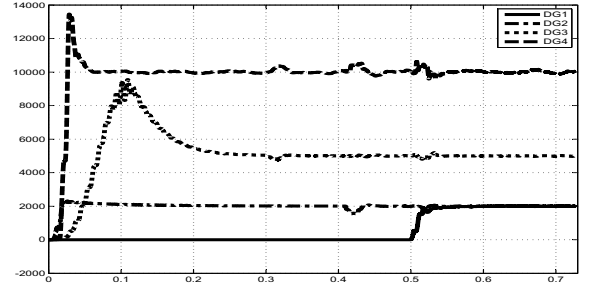


Fig. 9. Real power output of DGs

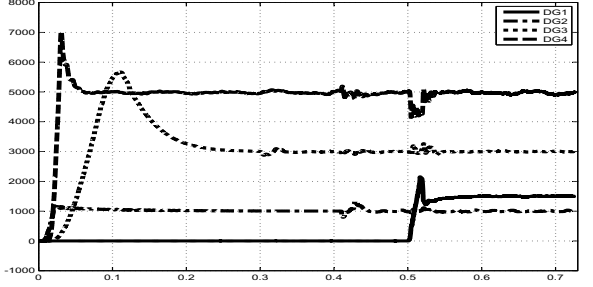


Fig. 10. Reactive power output of DGs

At $t = 0.5$ s, when the microgrid containing DG2, DG3 and DG4 is stable, connect DG1 and Load 1 to the microgrid.

Real power output of DGs is shown in Fig. 9. It can be seen from the figure that at time $t = 0.3$ s and 0.41 s, the connection transients of DG2 and DG3 are very small with pre-start and synchronizing process. Reactive power overshoot shown in Fig. 10 is also tuned by adopting pre-start, synchronizing process.

Total real and reactive power generation in microgrid is shown in Fig. 11. Compared with Fig. 12, it shows that microgrid with pre-start and synchronization process has smaller ripples when connecting new units; therefore, transients is more smooth and microgrid is more stable in black start procedure.

Voltage profile at bus 5 is shown in Fig. 13. At $t = 0.3$ s and 0.41 s, there are small ripples when connecting new units. These ripples can be reduced by improving performance of Phase Lock Loop (PLL). At $t = 0.5$ s, although DG

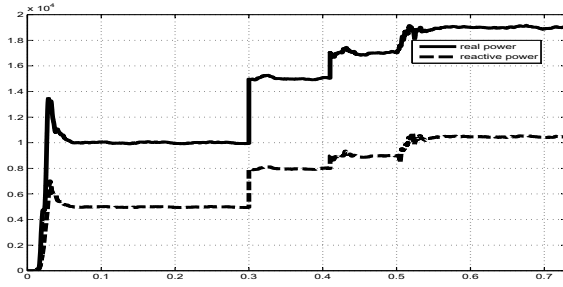


Fig. 11. Real and reactive power generation in microgrid

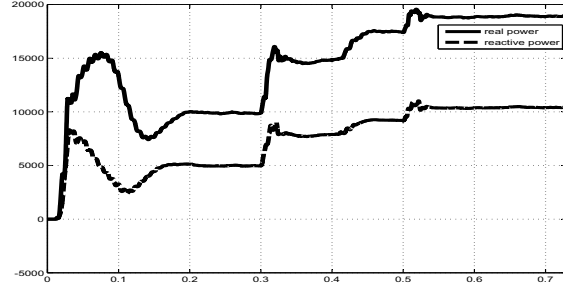


Fig. 12. Real and reactive power generation in microgrid without pre-start and synchronization process

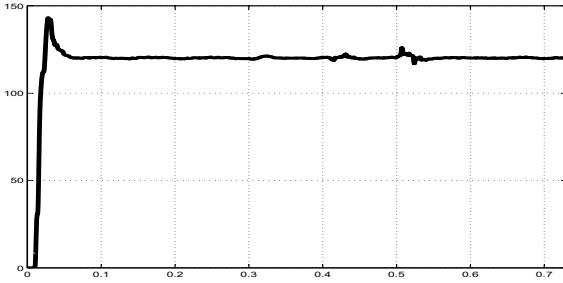


Fig. 13. Voltage in bus 5 of microgrid

1 is connected to microgrid without pre-started process, the system's capacity and tolerance of disturbance has been greatly enhanced by adding DG 2 and DG 3. As seen from the Fig. 13, the voltage is still able to maintain at $t = 0.5$ s with some small ripples. If DG 1 has voltage control mode and could pre-start and synchronize with microgrid, the ripples could be further tuned.

VI. CONCLUSION

Microgrid has complex operations resulting from its distinct characteristics from conventional large power system. This paper presents the feasibility of adopting a hierarchical architecture of multi-agent system in microgrid operation. Multi-agent system is chosen as an operator providing both intelligence to optimize algorithm and implementation capability to execute complicated tasks. Control strategies by multi-agent system for grid-connected operation and islanded operation of microgrid are discussed. A set of actions and procedures are identified in this paper for multi-agent system to conduct black start of microgrid. The results obtained in simulation prove that multi-agent system is effective to implement microgrid restoration.

Pre-start and synchronization process of distributed generations before connecting to a restoring microgrid could reduce the disturbance introduced by the connection and be prone to maintain the stability of microgrid.

REFERENCES

- [1] U.S. Department of Energy, Energy Information Administration-Independent Statistics and Analysis, "Annual Energy Outlook Early Release Overview," Report #DOE/EIA-0383, 2010, available at: <http://www.eia.doe.gov/oiaf/aeo/overview.html>.
- [2] R. Lasseter, "Microgrids," *Proceeding IEEE Power Engineering Society Winter Meeting*, 2002, pp. 305-308.
- [3] Qin Lei, Fang Z. Peng, and Irvin J. Balaguer, "Islanding Control of DG in Microgrids," *Power Electronics and Motion Control Conference*, Wuhan, China, May 2009, pp. 450-455.
- [4] Peng Li, Bin Song, Wei Wang and Tiemin Wang "Multi-agent approach for service restoration of microgrid," *Industrial electronics and applications (ICIEA)*, Taichung, Taiwan, June, 2010, pp. 962-966.
- [5] Shouxiang Wang, Xiaojing Li, Zhaoxia Xiao and Chengshan Wang "Multi-agent approach for service restoration of distribution system containing distributed generations," *Automation of Electric Power Systems*, vol. 31, no. 10, pp. 61-65, 2007.
- [6] F. Katiraei, M. R. Iravani, "Power management strategies for a microgrid with multiple distributed generation units", *Power Systems, IEEE Transaction on*, vol. 21, no. 4, pp. 1821-1831, Nov. 2006.
- [7] Peng, F. Z., YunWei Li, L.M. Tolbert, "Control and Protection of Power Electronics Interfaced Distributed Generation System in a Customer-Driven Microgrid," *Power & Energy Society General Meeting*, Calgary, AB, July, 2009, pp. 1-8.
- [8] B. Kirkby, E. Hirst, "New blackstart standards needed for competitive markets," *IEEE Power Engineering Review*, vol. 19, no. 2, pp. 9-11, 1999.
- [9] N. A. Fountas, N. D. Hatziaargyriou, C. Orfanogiannis et al, "Interactive long-term simulation for power system restoration planning", *Power Systems, IEEE Transaction on*, vol. 12, no. 1, pp. 61-68, 1997.
- [10] J. W. Feltes and Carlos Grande-Moran, "Black start studies for system restoration," *Power & Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, Pittsburgh, PA, July, 2008, pp. 1-8.
- [11] C. L. Moreira, F. O. Resende and J. A. Peças Lopes "Using low voltage microgrids for service restoration", *Power Systems, IEEE Transaction on*, vol. 22, no. 1, pp. 395-403, Feb. 2007.
- [12] J. A. Peças Lopes, C. L. Moreira and F. O. Resende, "Microgrids black start and islanded operation," in *Power Systems Computation Conference - PSCC*, Liège, Belgium, Aug. 2005, pp. 1-7.
- [13] Niannian Cai and Joydeep Mitra, "A Decentralized control Architecture for a Microgrid with Power Electronic Interfaces" *Power Symposium, Proc. of the 42th Annual North American*, Alinton, TX, Sep. 2010.
- [14] M. Pipattanasomporn, H. Feroze, S. Rahman, "Multi-Agent systems in a distributed smart grid: design and implementation," *Power Systems Conference and Exposition*, Seattle, WA, March 2009, pp. 1-8.
- [15] Aris L. Dimeas, Nikos D. Hatziaargyriou, "Operation of a Multi-agent System for Microgrid Control", *Power Systems, IEEE Transaction on*, vol. 20, no. 3, pp. 1447-1455, 2005.
- [16] S. D. J. McArthur, E. M Davidson and V. M. Catterson et al, "Multi-agent systems for power engineering applications-part I: concepts, approaches, and technical challenges," *IEEE Trans. Power Syst.*, vol. 22, no. 4 pp. 1743-1752, Nov. 2007.
- [17] S. D. J. McArthur, E. M Davidson and V. M. Catterson et al, "Multi-agent systems for power engineering applications-part II: technologies, standards, and tools for Building multi-agent systems," *IEEE Trans. Power Syst.*, vol. 22, issue. 4 pp. 1753-1759, Nov. 2007.
- [18] M. E. Baran and I. M. Markabi, "A multi-agent-based dispatching scheme for distributed generators for voltage support on distribution feeders," *Power Systems, IEEE Transactions on*, Volume 22, Issue 1, pp. 52-59, 2007.
- [19] J. M. Solanki, N. N. Schulz and Wenzhong Gao, "Reconfiguration for restoration of power systems using a multi-agent system," *Power Symposium, Proc. of the 37th Annual North American*, Ames, Iowa, Dec. 2005, pp. 390-395.
- [20] J. A. Peças Lopes, A. G. Madureira, C. L. Moreira et al, "Control strategies for microgrids emergency operation," in *Future Power Systems, 2005 International Conference on*, Amsterdam, Nov. 2005, pp. 1-6.

- [21] C. González-Morán, P. Arbolea, G. Díaz et al, "Modelling Photovoltaic DC Primary sources as grid connected inverter supplies considering non linear effects," in *Electrical Power Conference* , Montreal, Canada, Oct. 2007, pp. 50.
- [22] Duan Yubing, Gong Yulei, Li Qingmin and Wang Hui, "Modelling and simulation of the microsources within a microgrid," in *International Conference on Electrical Machines and Systems*, Wuhan, China, Feb. 2009, pp. 2667.
- [23] H. Hosseinzadeh, X. Huang, and J. Jiang, "Simulation of micro-sources in a small scale microgrid," in *Power & Energy General Meeting*, Calgary, AB, July, 2009, pp. 1.
- [24] A. Roshan and R. Burgos, A.C. Baisden et al., "A D-Q frame controller for a full-bridge single phase inverter used in small distributed power generation systems," in *Proc. IEEE Applied Power Electronics Conference and Exposition - APEC*, Anaheim, CA, Feb. 2007, pp. 641-647.
- [25] Renata Carnieletto and S. Suryanarayanan, Marcelo G. Simões et al., "A multifunctional single-phase voltage source inverter in perspective of the smart grid initiative," in *Industry Applications Society Annual Meeting*, Houston, TX, Oct. 2009, pp. 1-7.

VII. BIOGRAPHIES

Niannian Cai (S '10) received his B.S. from Huazhong University of Science and Technology. He is currently pursuing a Ph.D. degree in Electrical Engineering at Michigan State University. His doctoral research focuses on microgrid architecture and multi-agent control of microgrids. His research interests include power system planning and control. (email: cainiann@msu.edu)

Xufeng Xu (M '11) was born in 1981 in Zhejiang, China. He received the B.E. degree and the Ph.D. degree in electrical engineering department from Zhejiang University, Hangzhou, China. He is currently a post-doctoral research assistant in ECE department at Michigan State University, East Lansing, USA. His research interests include power system reliability, power system planning and microgrid. (e-mail: eexxf@msu.edu)

Joydeep Mitra (S '94, M '97, SM '02) is Associate Professor of Electrical Engineering at Michigan State University, East Lansing. Prior to this, he was Associate Professor at New Mexico State University, Las Cruces, Assistant Professor at North Dakota State University, Fargo, and Senior Consulting Engineer at LCG Consulting, Los Altos, CA. He received a Ph.D. in Electrical Engineering from Texas A&M University, College Station, and a B.Tech. (Hons.), also in Electrical Engineering, from Indian Institute of Technology, Kharagpur. His research interests include power system reliability, distributed energy resources, and power system planning. (email: mitraj@msu.edu)