Task 1: Coupling Low-Voltage Microgrids into Mid-Voltage Distribution Systems

Zhao Wang, *Student Member, IEEE,* and Michael Lemmon, *Member, IEEE*

Abstract

This report presents results of the first two stages of the project, i.e. algorithm development and simulation model development. A hierarchical control architecture is proposed to maximize the real power export to mid-voltage (MV) distribution network by coupling low-voltage (LV) microgrids. At the same time, reactive power is dispatched coordinatively so that voltage regulatory constraints are satisfied. Two levels of optimization problems are solved to designate set points for each microsource controller: 1) the state at the point of common coupling (PCC) is determined by each microgrid controller in a decentralized fashion, 2) set points for microsources within a microgrid are calculated in the microgrid controller in a centralized way. Corresponding simulation model is developed in MATLAB® Simulink® with SimPowerSystems™ toolbox. Simulation results show that the algorithm developed can maintain system stability, while simultaneously achieving the goal of maximizing real power export under voltage regulation constraints. Response of the system under disturbances proves the robustness of the hierarchical control system.

Index Terms

Distributed optimization, capacity estimation, weak network.

I. Introduction

The power grid system is expected to see tremendous changes, one of which is a high level penetration of distributed energy resources (DERs) in LV distribution networks. DER is promoted as a means to meet the constantly increasing demand for high quality electric power, but it may cause as many problems as it solves [1]. Current power grid operates based on the unidirectional power flow assumption. Both control methods and protection mechanisms are designed to work with this assumption. A high penetration of DERs in distribution networks may result in power flow that move in the opposite direction to conventional flow situations. A "voltage rise problem" arises from the multi-directional power flows, when integrated DERs export real power back to the distribution network [2]. Because LV and MV segments of the power grid are weak, this problem is much more severe in these circumstances than in the high-voltage (HV) transmission network. Since our objective is coupling LV microgrids to MV distribution networks, we need to formulate and solve the voltage regulation problem assuming weak network connections.

Z. Wang and M. Lemmon are with the Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN, 46556, USA e-mail: wang.198@nd.edu.

We intend to maximize the real power export back to the MV distribution network from the coupled LV microgrids, while respecting regulatory constraints on voltage magnitude and frequency, transient stability in the face of faults, topology variations, or set point changes, as well as compatibility with legacy control devices in the distribution network.

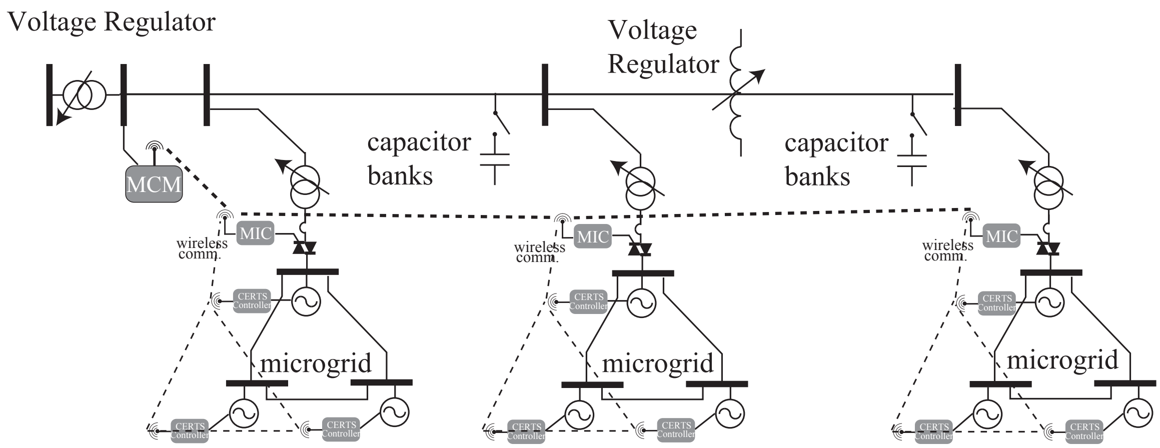


Fig. 1. Complete system model of hierarchical system

To realize this objective, a hierarchical control architecture is proposed as illustrated in figure 1. At the basic level of the multi-layer structure, we have microsource controllers tied to DERs within microgrids. These controllers ensure the multi-unit stability of the network for a selected set point provided by their upper level microgrid controller [5]. The MIC of a microgrid at the PCC designates a set point to each microsource controller satisfying PCC real power and voltage conditions. For the microgrid consortium, the microgrid consortium manager (MCM) functions as a supervisor. It determines status of the entire consortium, based on information from neighboring MICs. The MCM does not directly designate set points to the coupled microgrids, but lets each microgrid determine its own state. Each MIC maximizes its real power export through the PCC only using local information from its neighbors. Compared to the centralized control structure, the decentralized approach places less burden on the communication network, and it is also robust to system disturbances.

With the help of this hierarchical control architecture, the coupled microgrids provide not only real power service but also voltage control service to the distribution network. Voltage control is a kind of "ancillary services" that must be provided simultaneously with the transaction of power services [3]. Ancillary services are crucial for maintaining reliable operation of the power grid. Besides voltage control service, one can also provide load following, operating reserves, and energy imbalance with the same control system [4]. Then coupled microgrids would become a more active player in both power service and ancillary service markets. This would encourage the integration of DERs into the power grid.

Our work is only the first step of a comprehensive microgrid consortium controller. The next step is to let the coupled microgrids achieve a common real or reactive power objective, with the same decentralized control architecture. Because of the nonlinear and weak nature of the LV and MV distribution networks, this scheduling problem is yet solved. Therefore, the microgrid consortium is capable of providing more ancillary services than merely voltage control. Since both control layers are integrated in the MIC, this control architecture can be realized with actual microgrid controllers from GE®.

II. System Model

This section provides a detailed description of the distribution network model, as well as specifications and assumptions used in our algorithm development, simulation, and verification processes. Properties of this network are also identified, including its weak network connections and variable structure.

A. Distribution Network Model

Considering the hierarchical control architecture given in Section I, there are two layers of network model corresponding to the MV distribution network and the LV microgrid respectively.

1) Model of MV Distribution Network: The distribution network model is shown in figure 2. There are N buses in this network. Bus 1 is connected to the primary substation, hence represents the main grid. Microgrids or pure loads connected to the remaining $N-1$ buses are modeled as a microsource and a load tied to each bus. This modification is appropriate, because microgrids keep their real and reactive power levels during operation.

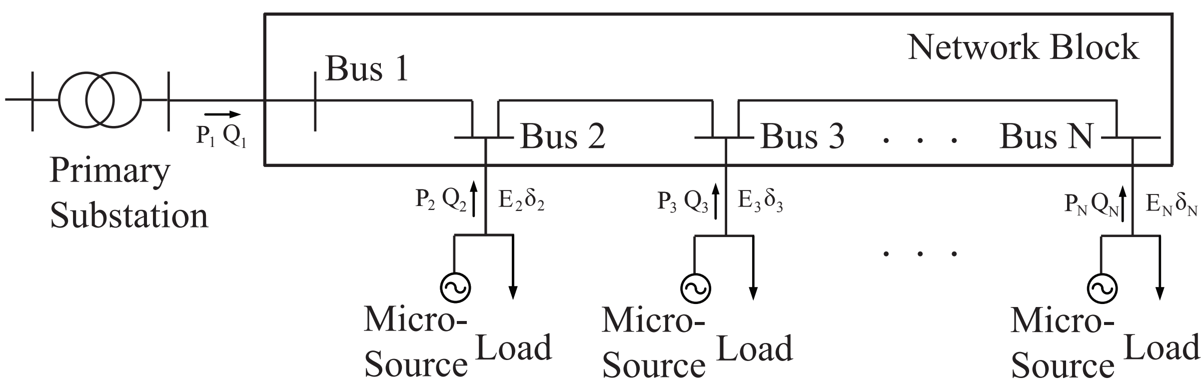


Fig. 2. MV distribution network model

Voltage magnitude and phase angle of bus i are E_i and δ_i. Specifically, bus 1 has $E_1 = 1.0\ pu$ and $\delta_1 = 0°$. Real and reactive power injected through bus i into the network are P_i and Q_i. Signs of P_i and Q_i represent the direction of power flows, where a positive value means power injection into the network.

2) Model of LV Microgrid: The microgrid controlled by the MICs is shown in figure 3. There are M buses in this microgrid. Bus 1 is connected to the PCC, and represents the input/output port of the microgrid. A microsource and a load are connected to each of the remaining $(M-1)$ buses.

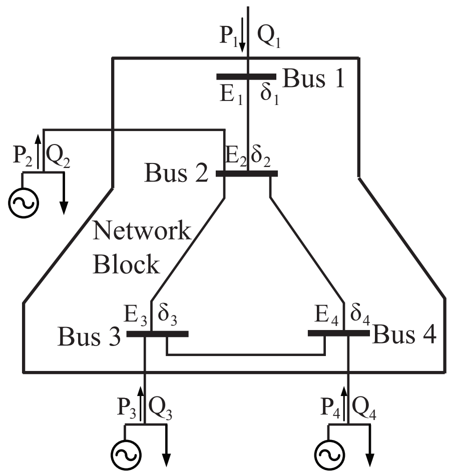


Fig. 3. LV microgrid model

Voltage magnitude and phase angle of bus i are E_i and δ_i. Real and reactive power injected through bus i into the network are P_i and Q_i. Signs of P_i and Q_i represent the direction of power flows, where a positive value means power injection into the microgrid. Specifically, bus 1 has $E_1 = E_i^*$ and $P_1 = -P_i^*$, i.e. the state determined for the PCC of the microgrid.

3) Expression of Real Power Loss: To express the real power loss P_{loss} over the connection lines, we define the "network block" in figure 2 and figure 3. The "network block" only incorporates distribution lines connecting all the buses. Because the block has no generation capability, it is a passive system and only capable of consuming power. This definition helps when we consider the total line loss in our optimization problem. The real power loss is the sum of real power injection into the network over all buses $P_{loss} = \sum P_i$.

B. Weak Network Property

Specifications of distribution lines is another very important aspect of our modeling. In contrast to HV transmission lines, LV and MV distribution lines have a nontrivial ratio of $\frac{R}{X}$, where R is line resistance and X is line reactance. This is usually called a "weak network", indicating its vulnerability to disturbances.

More importantly, the real and reactive power are coupled together. The expressions of real and reactive power export at bus i are as follows:

$$\begin{aligned} P_i &= E_i \sum E_j \left(G_{BUS,ij} \cos(\delta_i - \delta_j) + B_{BUS,ij} \sin(\delta_i - \delta_j)\right) \\ Q_i &= E_i \sum E_j \left(G_{BUS,ij} \sin(\delta_i - \delta_j) - B_{BUS,ij} \cos(\delta_i - \delta_j)\right) \end{aligned}$$

It is unable to linearize the equations above without making assumptions about the connections, i.e. $G_{BUS,ij}$ and $B_{BUS,ij}$ in the expressions above. As a result, we consider weak systems with coupled real and reactive power control in our analysis and algorithm development.

C. Structural Variation

In the electric power grid, structural variations are caused by switching operations. Because of the control and protection operations conducted in distribution networks, the system structure is frequently changing. Such changes have a direct impact on our hierarchical control system, since all set points are determined based on network information.

Before responding to the structural changes, we have to detect them. Switchings happening within microgrids are usually tractable by MICs, while switchings in MV distribution network are detectable by the MICs connected by those corresponding links.

With the hierarchical control structure, responses to those structural changes can be confined to the corresponding control layer. For instance, when the connection topology within a microgrid changes, it can be detected by its MIC and used to update optimization problems, and then set point modifications can be designated. If the set point before structural changes is still achievable by the microgrid, then disturbances will have no influence on system operation beyond this microgrid.

III. Approach

The hierarchical control system structure consists of low-level microsource controllers, mid-level MICs, and a high-level MCM, as shown in figure 1. The control algorithm, however, is realized in the MICs. The objective is to maximize the real power export from coupled microgrids with the proposed hierarchical control architecture. Three aspects of problems are identified and solved in MICs, including decentralized control among coupled microgrids, set point determination of microsources within microgrids, and microgrid capacity estimation.

A. Decentralized Control among Coupled Microgrids

The objective of the MIC optimization problem is to maximize real power export from this microgrid, and minimize the real power loss along the distribution lines connected to it. The optimization subjects to constraints on microgrid generation capacities, MV line power flow limits, regulatory constraints on voltage and frequency. Solutions to this problem are the real power and voltage levels at the PCC. This set point can then be implemented as constraints to solve another optimization problem to determine microsource set points. For bus i, assuming there are M buses and L lines connecting them on the MV distribution network. This optimization problem is expressed as:

$$
\begin{aligned}
Minimize \quad & P_{mg,i} + P_{loss,i} \\
& = E_{mg,i} \sum_{j=1}^{M} E_{mg,j} \left(G_{BUS,1j} \cos(\delta_{mg,1} - \delta_{mg,j}) + B_{BUS,1j} \sin(\delta_{mg,1} - \delta_{mg,j}) \right) + P_{loss,i} \\
w.r.t. \quad & E_{mg,i} \quad P_{mg,i} \\
subject \quad to \quad & Generation \quad Capability \quad Constraints \quad (i = 2, 3, \cdots, M) \\
& \underline{P_{mg,i}} \leq P_{mg,i} \leq \overline{P_{mg,i}} \\
& \underline{Q_{mg,i}} \leq Q_{mg,i} \leq \overline{Q_{mg,i}} \\
& Power \quad Flow \quad Constraints \quad (i = 1, 2, \cdots, L) \\
& \underline{P_{ln,i}} \leq P_{ln,i} \leq \overline{P_{ln,i}} \\
& \underline{Q_{ln,i}} \leq Q_{ln,i} \leq \overline{Q_{ln,i}} \\
& Voltage \quad Regulation \quad Rule \quad (i = 2, 3, \cdots, M) \\
& \underline{E_{mg,i}} \leq E_{mg,i} \leq \overline{E_{mg,i}} \\
& Power \quad Balance \quad Relationship \quad at \quad PCC \\
P_{mg,i} \quad = \quad & E_{mg,i} \sum E_{mg,j} \left(G_{BUS,ij} \cos(\delta_{mg,i} - \delta_{mg,j}) + B_{BUS,ij} \sin(\delta_{mg,i} - \delta_{mg,j}) \right) \\
Q_{mg,i} \quad = \quad & E_{mg,i} \sum E_{mg,j} \left(G_{BUS,ij} \sin(\delta_{mg,i} - \delta_{mg,j}) - B_{BUS,ij} \cos(\delta_{mg,i} - \delta_{mg,j}) \right)
\end{aligned}
$$

In the optimization problem above, we need to compute $P_{loss,i}$ and the power flowing into bus i based on set points of its neighboring buses. The power flows from bus i to bus j and in the reverse direction are:

$$
\begin{aligned}
P_{ij} &= -E_{mg,i}^2 G_{BUS,ij} + E_{mg,i} E_{mg,j} \left(G_{BUS,ij} \cos(\delta_{mg,i} - \delta_{mg,j}) + B_{BUS,ij} \sin(\delta_{mg,i} - \delta_{mg,j}) \right) \\
P_{ji} &= -E_{mg,j}^2 G_{BUS,ji} + E_{mg,j} E_{mg,i} \left(G_{BUS,ji} \cos(\delta_{mg,j} - \delta_{mg,i}) + B_{BUS,ji} \sin(\delta_{mg,j} - \delta_{mg,i}) \right)
\end{aligned}
$$

Based on the two power flow expressions, the real power loss along the line between bus i and bus j is $P_{ij,loss} = P_{loss,ij} = | - G_{BUS,ij}(E_{mg,i}^2 - E_{mg,j}^2) + 2B_{BUS,ij} sin(\delta_{mg,i} - \delta_{mg,j}) E_{mg,i} E_{mg,j}|$. For the bus closest to the primary substation, the line loss between it and the slack bus must be doubled. So that the sum of all the objective functions within the distribution feeder would be the same as the one used in a centralized optimization problem.

By solving this optimization problem, the real power export to the distribution feeder is maximized, subject to constraints on microgrid generation capacities, MV line power flow limits, regulatory constraint on voltage and frequency. Since the microgrids are in close proximity, we can operate a communication network to exchange state information between neighboring microgrids. The information required to solve this optimization problem is only the voltage magnitude and phase-shift of directly connected microgrids.

B. Microsource Set Points Determination

The MIC maintains the set point determined above, and determines set points of the microsources within its microgrid. The set points are determined by solving an optimization problem, which aims to minimize the microgrid running cost.

The objective of the MIC optimization problem is to minimize the generation costs while maintaining the given set point at the PCC. The optimization is done subject to constraints on microsource generation capacities, LV line power flow limits, regulatory constraints on voltage and frequency, and states at the PCC. Solutions to this problem are the real power and voltage set points, as introduced in Section II. These set points are directly fed to the microsource controllers as inputs. Assuming there are M buses and L lines connecting them, this optimization problem is expressed as:

$$
\begin{array}{rcl}
Minimize & & C\left(\sum_{i=2}^{M} P_{ms,i}\right) \\
w.r.t. & & E_i \quad P_{ms,i} \quad (i = 2, 3, \cdots, M) \\
subject \quad to & & Generation \quad Capability \quad Constraints \quad (i = 2, 3, \cdots, M) \\
& & \underline{P_{ms,i}} \leq P_{ms,i} \leq \overline{P_{ms,i}} \\
& & \underline{Q_{ms,i}} \leq Q_{ms,i} \leq \overline{Q_{ms,i}} \\
& & Power \quad Flow \quad Constraints \quad (i = 1, 2, \cdots, L) \\
& & \underline{P_{ln,i}} \leq P_{ln,i} \leq \overline{P_{ln,i}} \\
& & \underline{Q_{ln,i}} \leq Q_{ln,i} \leq \overline{Q_{ln,i}} \\
& & Voltage \quad Regulation \quad Rule \quad (i = 2, 3, \cdots, M) \\
& & \underline{E_i} \leq E_i \leq \overline{E_i} \\
& & Power \quad Balance \quad Relationship \quad (i = 1, 2, \cdots, M) \\
P_i & = & E_i \sum E_j \left(G_{BUS,ij} \cos(\delta_i - \delta_j) + B_{BUS,ij} \sin(\delta_i - \delta_j)\right) \\
P_i & = & P_{ms,i} - P_{load,i} \\
Q_i & = & E_i \sum E_j \left(G_{BUS,ij} \sin(\delta_i - \delta_j) - B_{BUS,ij} \cos(\delta_i - \delta_j)\right) \\
Q_i & = & Q_{ms,i} - Q_{load,i}
\end{array}
$$

where $C(\cdot)$ is the cost function of running the microgrid, primarily the cost of power generation.

Since the microgrid concept organizes microsources in close proximity, we can operate a communication network to transmit set points and to update topology and parameter changes. This optimization problem is solved numerically in a centralized fashion, and set points are transmitted locally through a wireless communication network. The set point information designated to each microsource includes real power and required voltage values.

C. Microgrid Capacity Estimation

In the hierarchical control architecture, the microgrid capacities are used as constraints in the optimization problems above, hence the real and reactive power capacity range must be identified for each microgrid. This capacity is obtained by solving a series of optimization problems, and then selecting a subset of the applicable region to ensure achievability.

Real and reactive power capacity must be determined over the voltage between $0.95pu$ and $1.05pu$. First, the reactive power range is determined, based on the optimization problem of maximizing and minimizing reactive power export. At the extreme value of reactive power export, the maximum and minimum real power export capacities are obtained from another set of optimization problems with such reactive power constraints.

To select the microgrid capacity achievable with any PCC voltage between $0.95pu$ and $1.05pu$, we need to assume that the region determined by the optimization problems above is convex. To simplify this procedure, the PCC voltage is set to be $0.95pu$, $1.0pu$ and $1.05pu$. The real power range is determined by finding the average maximum and minimum real power achievable with those three voltage levels. Although the power range is conservative, it guarantees that every set point inside the region is achievable by the microgrid.

D. System Operation Procedure

With the system architecture shown in figure 1, a typical system operation procedure is described.

The MIC solves an optimization problem to maximize the real power injected by its microgrid through the PCC, while considering the microgrid's capacity, MV distribution line power flow constraints, and voltage regulation along the line. The solution to this optimization problem is the state at the PCC. This state serves as a constraint for another optimization problem also solved by the MICs, with constraints concerning the microsource's capacity, line flow limits within the microgrid, and regulatory constraints on voltage and frequency. This optimization problem seeks to minimize the operational cost of the microgrid. Its output is a collection of voltage and real power set points of microsources within the microgrid. These set points are transmitted to microsource controllers instantly. The basic level microsource controllers use the real power and voltage set points as inputs, and actively adjust network frequency and reactive power to maintain voltage and frequency stability during operation.

When component parameters or network topologies change, the microsource controllers should inform the MICs about the changes that have happened. After updating its system model, the MIC recalculates the capacity of the microgrid. The new capacity information is then sent to the MIC and used to recalculate the optimal solution for the entire system.

IV. Simulation Results

This section provides the simulation results of the hierarchical control architecture in a distribution network with coupled microgrids. In addition to steady state operations, system behaviors under structural disturbances are also demonstrated. It is shown that the multi-layer control system is able to robustly respond to switching operations happening in distribution networks.

A. Simulation Model

The complete system architecture shown in figure 1 is integrated into the distribution network. In a three-bus distribution network, each of the two microgrid buses accomodates a Δ-connected microgrid, as shown in figure 4. Lines' parameters are shown in table I.

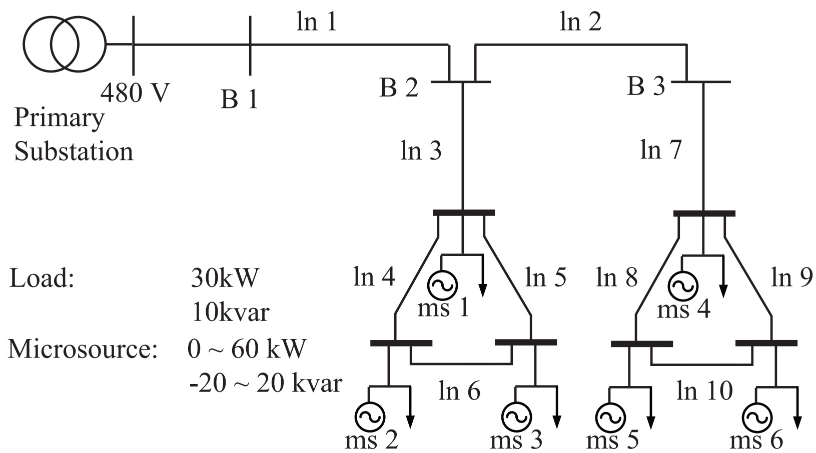


Fig. 4. Microgrid Simulation Model Schematic Model

TABLE I
LINE PARAMETERS OF DISTRIBUTION NETWORK

Line	Type	Voltage (V)	Length (mile)	R (Ω)	X (Ω)
ln 1	AWG 1	480	1	0.786	0.156
ln 2	AWG 1	480	0.5	0.393	0.078
ln 3	AWG 1	480	0.2	0.1572	0.0312
ln 4	AWG 4	480	0.2	0.316	0.035
ln 5	AWG 4	480	0.2	0.316	0.035
ln 6	AWG 4	480	0.2	0.316	0.035
ln 7	AWG 1	480	0.2	0.1572	0.0312
ln 8	AWG 4	480	0.2	0.316	0.035
ln 9	AWG 4	480	0.2	0.316	0.035
ln 10	AWG 4	480	0.2	0.316	0.035

Structural changes are also included in this simulation model. Each connection line is controlled by a switch, hence there are various combinations of system topologies available. In this section, we will show the hierarchical controller's response to both structural changes within microgrids and on the lines connecting these microgrids. The system not only maintains stable operation, but also converges to an optimal state.

The corresponding complete simulation model is built with SimPowerSystems$^{\text{TM}}$ toolbox, as shown in figure 5. At each bus within a microgrid, there is a microsource with real power capacity between $0kW$ and $60kW$, and reactive power capacity between $-20kvar$ and $20kvar$. In addition, a load is consuming $30kW$ real power and $10kvar$ reactive power.

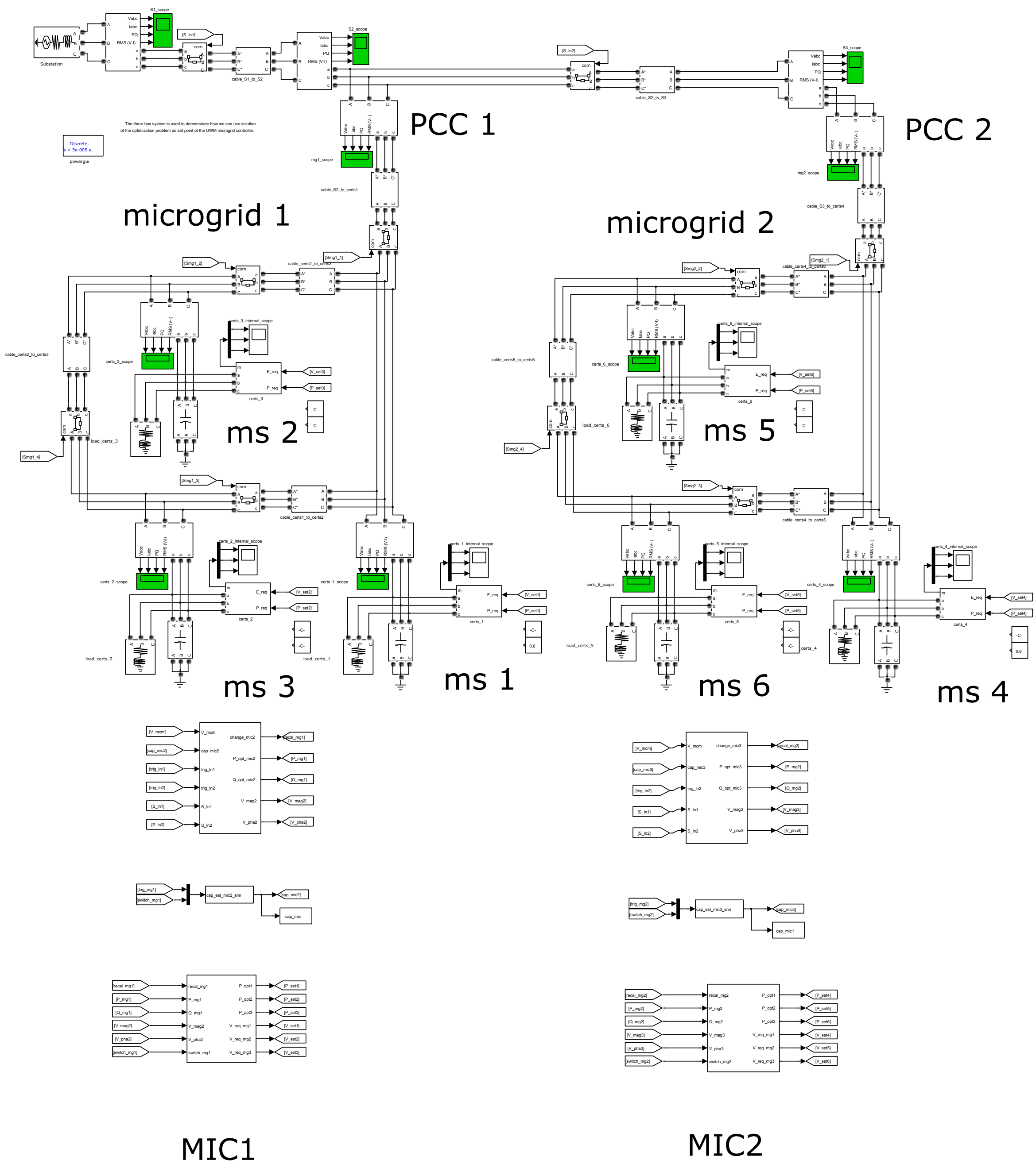


Fig. 5. Complete simulation model in Matlab with simpower toolbox

B. Steady State Operation

Our hierarchical control structure is capable of stabilizing the distribution network. The states of the system converges to the steady state in less than one second, as shown in figure 6. The decentralized optimization problem described in section III converges after 48 iterations, equivalent to $2.5ms$. Since this is even less than one period of AC electricity, performance of the decentralized system is satisfactory.

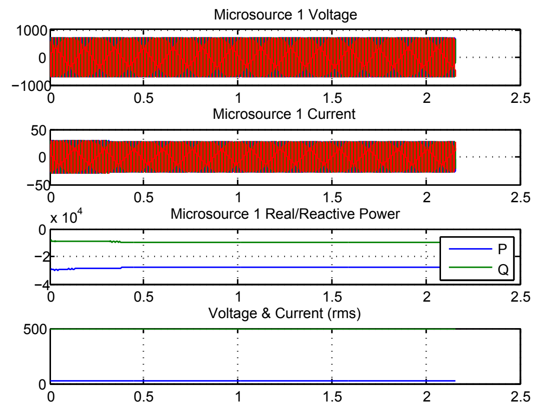


Fig. 6. Microsource Steady State Scope

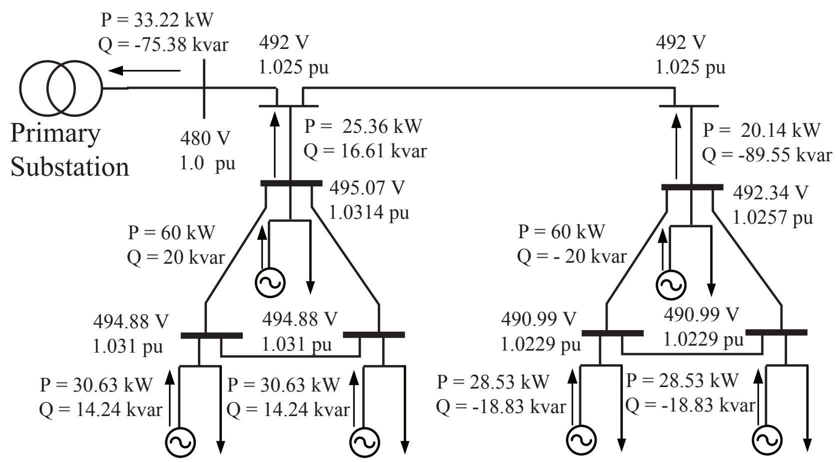
Figure 6 demonstrate the state of microsource "ms1". At the beginning, voltage, current, real and reactive power all show oscillations. After one second, the system states converge to the set point designated by MICs. The system steady state is shown in figure 7. In addition to support all the local loads, the coupled microgrids export $33.22kW$ real power to and require $75.38kvar$ reactive power from the main grid. With our hierarchical control system, the coupled microgrids not only support local loads, but also provide real power services to the distribution network.

The total amount of real power export to the distribution network is less than the maximum real power that can be extracted from the coupled microgrids. This reduction, however, is the result of our multi-layer architecture. A microgrid is able to export more real power, but the capacity range in higher level algorithm may not be guaranteed. With this sacrifice of microgrid capacity, system robustness can be improved. System operation under disturbances are shown in the rest of this section.

C. Operations under Disturbances

Distribution networks are vulnerable to frequent switchings, and system stability may be jeopardized by these typical operations. System response under network structural changes are considered in two aspects. The first case is for structural changes within microgrids, and the second also includes changes to distribution lines connecting the microgrids.

1) Changes within Microgrids: Changes are applied to the connection lines within microgrids. Line ln5 is disconnected at $t = 1s$, and line ln8 is disconnected at $t = 2s$. Responses of the two microgrids are shown in figure 8.



	ms 1	ms 2	ms 3	ms 4	ms 5	ms 6
P_{req}	60 kW	30.63 kW	30.63 kW	60 kW	28.53 kW	28.53 kW
E_{req}	1.0414 pu	1.0381 pu	1.0381 pu	1.0157 pu	1.0135 pu	1.0135 pu

Fig. 7. Distribution Network Steady State Simulation Result

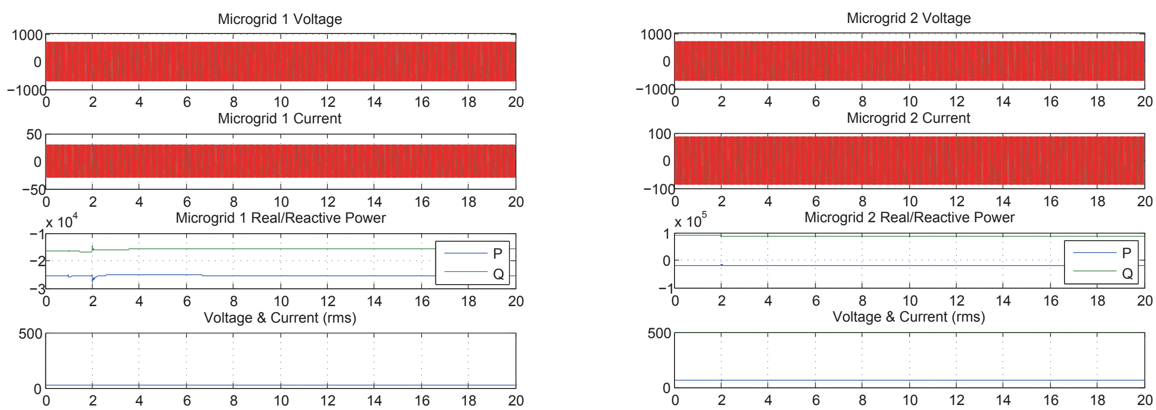


Fig. 8. Microgrid 1 and 2 Response to Changes within Microgrids

It is demonstrated that the real and reactive power injected by each microgrid change little after the switching operations. Both the microgrids are stabilized after those changes within one second. Furthermore, the voltage variations of participating microsources are all within 5% throughout the simulation process, as shown in figure 9. As a result, the hierarchical control system is robust to structural changes within microgrids. In this simulation, since the microgrid set point is still achievable after the disturbances, the MICs only reconfigure the interior of the microgrid to maintain PCC state.

2) Changes Outside Microgrids: In addition to the changes discussed in the previous simulation, changes are also applied to the connection lines between microgrids. Line “ln5” is disconnected at $t = 1s$, and line ”ln8” is

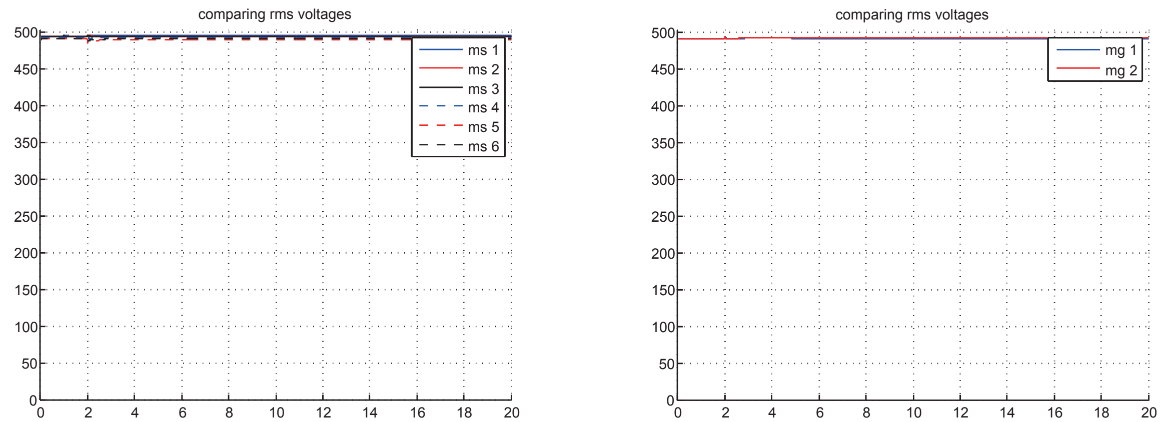


Fig. 9. Voltage Responses to Structural Changes within Microgrids

disconnected at $t = 5s$. The line between “mg1” and “mg2” is disconnected at $t = 10s$. Responses of the two microgrids are shown in figure 10.

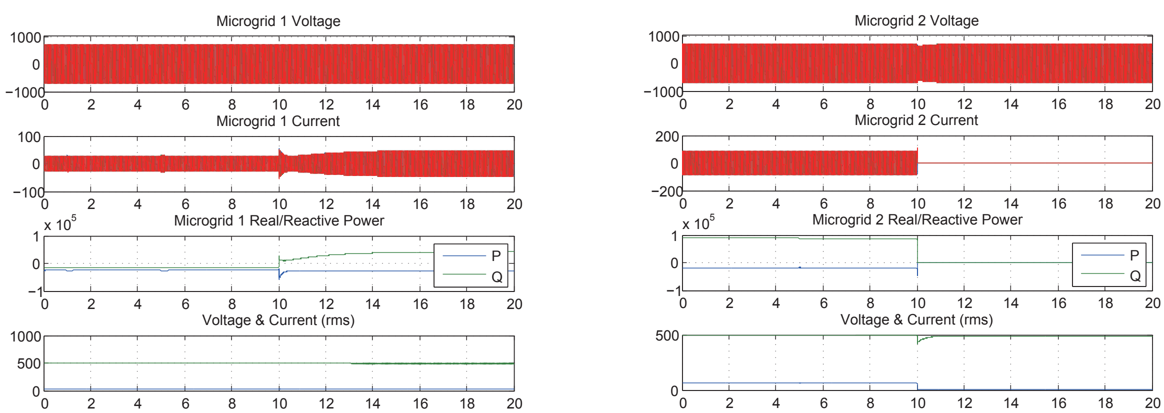


Fig. 10. Microgrid 1 and 2 Response to Changes Outside Microgrids

It is demonstrated that the real and reactive power injected by each microgrid change fundamentally. After “ln2” is disconnected, the two microgrids needs about six seconds to converge to the new set points designated by the hierarchical control system, as shown in figure 11. From figure 10, the power export by microgrid “mg2” is reduced to zero. Although the microgrid is disconnected from the network, it is still operating to support its local loads.

At the beginning of the system operation, there are 48 iterations of computation required to converge to the steady state. After structural changes to connection lines between microgrids, the decentralized controller only needs to exchange state information with neighboring agents once. Since the hierarchical control system converges soon after

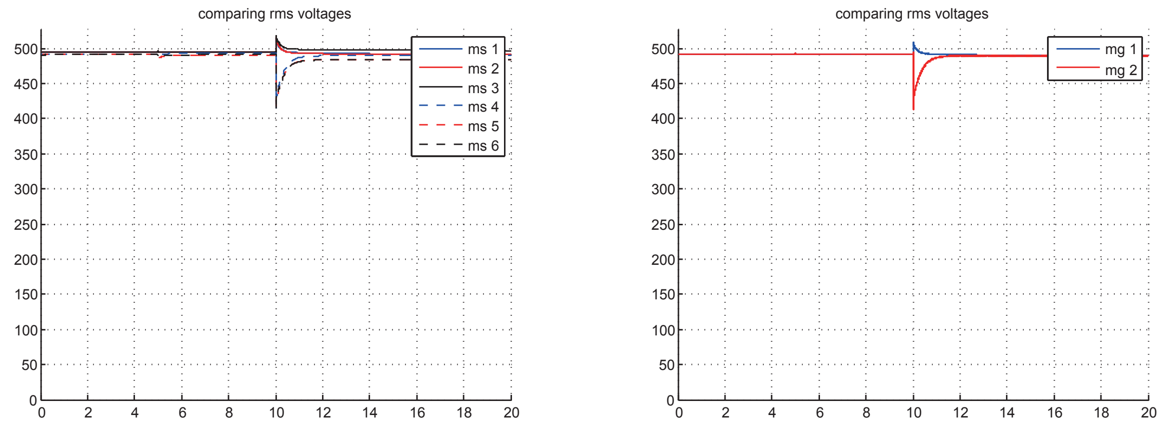


Fig. 11. Voltage Responses to Structural Changes Outside Microgrids

system variations, the communication burden of our controller is reasonable. More importantly, simulation results show that the hierarchical control system is robust to structural changes in the distribution network, both inside and outside of the microgrids.

V. Conclusion and Future Work

In this report, a multi-layer hierarchical control system is proposed, which consists of basic level microsource controllers, mid-level MICs, and a high level MCM. Microsource controllers ensure the multi-unit stability of the network for a selected set point provided by their upper level microgrid controller. The MIC of a microgrid connected to the PCC designates a set point to each microsource controller, satisfying the real power and voltage level demanded. The MCM determines the operation status of the entire consortium, based on information from neighboring MICs. The MIC not only determines its own state at the PCC, but also designate set points for microsources within the microgrid. Compared to the centralized control structure, the decentralized approach places less burden on communication networks, and it is also robust to disturbances in the distribution network.

With the help of this hierarchical control architecture, the coupled microgrids provide voltage control services in addition to the real power services to the distribution network. This report is actually only the first step of a comprehensive microgrid consortium controller. The next step is to let the coupled microgrids achieve a common real or reactive power objective. Then besides voltage control service, one can also provide load following, operating reserves, and energy imbalance services with the same control system. Then coupled microgrids would become a more active player in both power service and ancillary service markets. Since both control layers are integrated in the MIC, this control architecture can be realized with actual microgrid controllers from General Electric.

References

[1] Lasseter, R.H.; , "Smart Distribution: Coupled Microgrids," Proceedings of the IEEE , vol.99, no.6, pp.1074-1082, June 2011 doi: 10.1109/JPROC.2011.2114630.

[2] Masters, C.L.; , ”Voltage rise: the big issue when connecting embedded generation to long 11 kV overhead lines,” Power Engineering Journal , vol.16, no.1, pp.5-12, Feb. 2002 doi: 10.1049/pe:20020101.

[3] Hirst, E.; Kirby, B.;, ”Electric-Power Ancillary Services,” Oak Ridge National Laboratory, Feb. 1996 ORNL/CON-426.

[4] ”Promotes Wholesale Competition through Open Access and Non-Discriminatory Transmission Service by Public Utilities,” Federal Energy Regulatory Commission, RM95-8-000.

[5] Lasseter, R.; Piagi, P.; , ”Control and Design of Microgrid Components,” University of Wisconsin-Madison, January 2006.