Coordinated Control of Distributed Energy Resources and Conventional Power Plants for Frequency Control of Power Systems

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***Abstract*—Recently, distributed energy resources (DERs) are becoming more attractive to supply local loads under concept of microgrids. These new parts of the power system have basically different dynamics compared with conventional power plants (CPPs). Some of them do not have any rotating inertia and most of them are connected to the grid by power electronic interfaces. Stability and control of microgrids and the entire power system containing DERs and CPPs is one of the most important challenges of the recent power systems. Interactions between microgrids in grid-connected mode and CPPs should be coordinated to ensure and improve the stability of power system. In this paper, the effect of the increased penetration of DERs on the load frequency problem of power system is studied. Basically, synchronous generators of CPPs determine the dynamic behavior of power system for frequency control and are responsible to compensate load changes of the system. With the high penetration of DERs, these new parts can contribute in the frequency control. It is shown that with appropriate control of DERs in microgrids, the frequency deviation of the power system will decrease and the stability margin can be increased.**

***Index Terms*—Automatic generation control, frequency control, load frequency control, microgrid, smart grid, voltage source convertor.**

I. Introduction

FREQUENCY of a power system depends on power system active power balance and should remain nearly constant in different operating conditions. Frequency is a common parameter throughout the system and a change in active power generation or demand at one bus affects the whole system frequency [1].

Considering environmental and technical merits, utilizing distributed energy resources (DERs) is being more attractive in the smart grid environment. The most of DERs are interfaced to the grid via controlled power converters [3]. Increasing the integration of power electronics interfaced DERs makes them a flexible and important part of the power system [4].

The microgrids facilitate high depth of penetration of DER units and relay on information and communication technology (ICT) and advanced sensors and control/protection strategies and therefore they can be considered and exploited as the main building block of smart grid [5]. To enable them as a building block of the smart grid, the proposal of control, protection and power management strategies, based on the use of communication and monitoring of system components, is necessary [5].

Different DERs, electric vehicles, smart homes, and controllable loads can be integrated in a microgrid. Utilizing generation and storage units in a microgrid, can transform the distribution system from a passive network to active one. Different operation modes, load, and generation uncertainties and unpredictable disturbances cause complexities for the control and management of the microgrid. Such a system needs different control strategies in comparison with conventional power systems [6].

Fig. 1 shows a microgrid consisting of energy units, storage devices, and loads.

Voltage source converters (VSCs) have been proposed for interfacing some types of distributed generations (DGs) to distribution grid as shown in Fig. 2. Fast dynamic response, accurate performance, ease of implementation, and its inherent closed loop control to guarantee the required operating point are some of their advantages [7]. Each inverter-based DG system may have an energy source system, a grid-interfacing VSC, and output LC filters.

The microgrid can operate in grid-connected or islanded mode. In the grid-connected operation mode, the microgrid is connected to the grid at the point of common coupling (PCC), and each DG unit generates proper real and reactive power [8].

The high penetration of DERs mainly changes the dynamic behavior of the power system. Some of them, connected by converters to the grid, do not have any rotational inertia.

DERs are synchronized by phase-locked loop (PLL) with the grid frequency and follow the frequency variations. Their time constant is less than the mechanical time constant of conventional power plants. So, an appropriate control strategy can be applied to incorporate DERs in power system frequency control. Main differences of DERs in comparison with conventional power plants are as follows.

1) They are installed in distribution network.
2) The capacity of each DER is very small.
3) Their dynamic is very fast.

Storage systems can improve the performance of this system to supply required active power determined by the control system. It means that DERs may also be responsible for frequency control in power system in grid-connected mode and therefore, a control system should coordinate them with the

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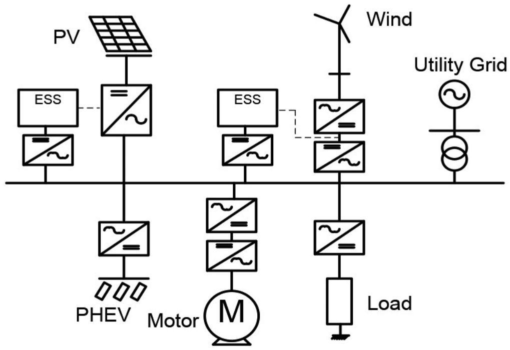

Fig. 1. Sample microgrid system.

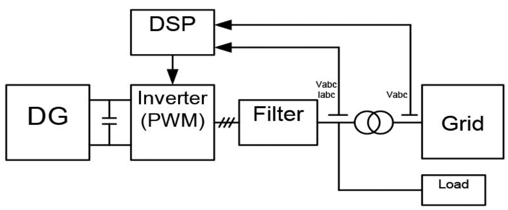

Fig. 2. Connection of DG to grid through VSC.

conventional load-frequency control (LFC). The contribution of electric vehicles (EV) and controllable loads in automatic generation control (AGC) has been presented in [9] and [10]. Masuta and Yokuyama [11] have focused on the application of EVs and heat pump water heaters in LFC. In [12]–[15], a coordinated control has been applied to doubly fed induction generators (DFIGs) to decrease the frequency deviation in both transient and steady state conditions. Contribution of high penetrated variable speed wind turbines in LFC is studied in [16]–[19]. The application of battery systems and superconductive magnetic energy storage (SMES) for AGC has been studied in [20] and [21], respectively. However, the contribution of highly penetrated DERs in LFC of power systems has not been studied yet. In this paper, the microgrids are responsible for the injected power exchange in distribution system. The contributions of this paper are as follows:

1) coordinated control of DERs in microgrids to contribute in LFC;
2) combination of DERs and loads in LFC; and
3) increasing the load-damping constant (D) of power system with the proposed control of microgrids.

The brief outline of the paper is as follows: Section II presents the LFC problem in power system. Section III describes the control strategy of DERs in microgrid and their response to frequency deviation. Section IV contains the simulation results and the conclusion is drawn in the last section.

II. Frequency Control in Power System

AGC is a common structure for matching the area generation to the area load and controlling the power system frequency [2]. A small change in the system load produces proportional changes in the system frequency. Based on the area control error (ACE) in each area, the supplementary controller manipulates the turbine settings of steam (gates of hydro) units to reduce ACE to zero [1].

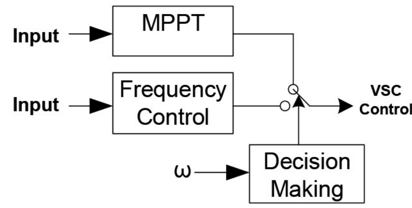

Fig. 3. Two control modes of VSC.

During the power system normal operation mode, only small deviations occur in the load and therefore linear models can be acceptable for representing the system dynamics around the operating point. In each control area, the generators are merged to form a coherent group. The load changes affect frequencies in all areas and tie-line power exchange among areas. The LFC should reduce the area frequency deviation to zero, and control the tie-line power exchange, so that the demand and generation reach to a new stable equilibrium point [22].

The inordinate drop in synchronous speed can cause the system to cascaded failure. Therefore, for a stable operation, the grid frequency must be effectively controlled. The AGC should control the frequency in response to load and generation changes by opening (closing) the turbine valves.

In this paper, the same idea is used to consider a coherent DG connected through VSC to the power system. It should be said that there are some differences between conventional generators and DGs but for the frequency control, the injected active power plays the same main role.

It is assumed that in the grid-connected mode, the reactive power, and voltage are regulated by controllers. Also, some methods have been proposed to decouple active and reactive powers in microgrids [23]–[25]. The total injected active power can be controlled in DGs to increase the frequency stability of the system. Therefore, a coordinated control is needed to change the injected active power in accordance with frequency deviations.

A. Modeling of Frequency Droop

As a power plant, the droop characteristic can be implemented for each DG with appropriate control system. It is assumed that each microgrid has a control system to implement the droop characteristic [7], [27]–[29]. In steady state condition, DERs are not responsible for frequency control. Some of them should follow the maximum power point tracking (MPPT) strategy adjusted by their local controller. A decision making system is needed to change the active power control mode of DERs from MPPT to frequency control mode as shown in Fig. 3.

After a disturbance, their function is important to decrease frequency deviations in both primary and secondary control. As the power change of DERs is based on the power control by convertors which have electrical time constant, they can react faster than mechanical systems of conventional power plants. Flexible alternating current transmission systems (FACTS) devices are also used in power systems and they can improve the stability of the system and decrease frequency deviations by proper control function. For example, thyristor control series capacitor (TCSC) and static compensator

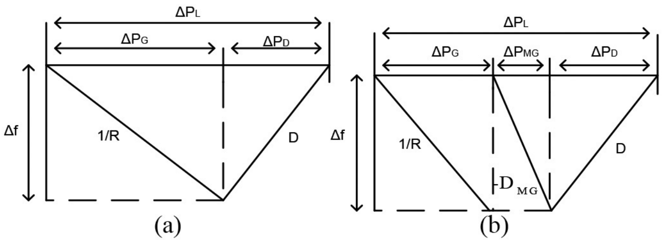

Fig. 4. Incorporating DERs in frequency droop. (a) Conventional power system (b) with contribution of microgrids.

(STATCOM) can be used to change the power transfer capability in transmission lines and control accelerating torque in synchronous generators [30].

The effect of DERs can be considered as a power source with the capability of rapid changes in distribution network. Physically, some limitations might exist to change the injected active power of DERs. These limitations depend on the type of the generation unit or the primary energy source. Using energy storage systems (ESSs), a rapid power change will be possible for the primary frequency control. It should be noted that controllable loads can also contribute in frequency control with appropriate control actions [31], [32]. As the amount of the power change after a disturbance is unknown, the droop control is adjusted based on power system frequency deviation. Power electronic converter based DERs can follow these oscillations with a fast dynamic and change their active power using the mentioned droop. Also, the conventional AGC is used for LFC but a coordinator adds a supplementary signal to the unit setpoints. In this paper, microgrids are considered as building blocks to contribute in frequency control. A similar concept is proposed for DERs as virtual power plant (VPP) to contribute in planning and power management [33], [34]. A central controller can be implemented in microgrid to manage DERs and loads to have arbitrary dynamic behavior and inject required active power at PCC. The main difference of this equivalent power plant with coherent generators in conventional AGC is its installation place which is in distribution system. High penetration of these frequency-dependent microgrids can affect LFC, significantly.

From the HV side of transformer, DERs can be considered as a variable load, which can be even negative. In conventional power systems, the frequency dependent loads have been modeled by load-damping constant (D) in electrical load model. In this paper, microgrids beside loads are both considered as controllable loads and their dynamics are determined by converters of DERs. The load characteristics are not controllable but DERs are controllable. So, D is not a constant coefficient and has a controllable dynamic in the system model. Its dynamic is determined by the controller of VSCs.

First, it is assumed that all DERs are adjusted to change their active power with a constant frequency droop and microgrids have the same constant droop characteristic. It means that a constant is added to the damping coefficient of loads in each area. Fig. 4(a) shows the generation and load change after a frequency deviation (△f).

In this figure, ($\triangle P_G$) is the change in the total generation of conventional generators due to their governor action.

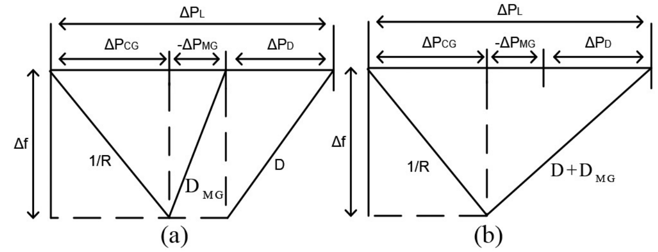

Fig. 5. Incorporating DERs in frequency droop. (a) Separate model. (b) Combination with loads.

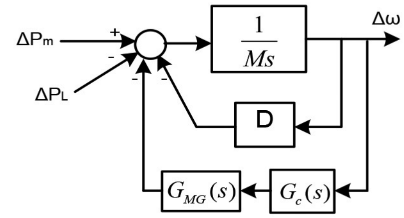

Fig. 6. Block diagram of system with DER controller.

Also, ($\triangle P_L$) is the increased (or decreased) load and ($\triangle P_D$) is the frequency-dependent load change. As shown in this figure, ($\triangle P_L$) causes frequency deviation (△f). This frequency deviation triggers governor and turbine of conventional generators to compensate the load change with the slope 1/R. Also, frequency dependent loads are changed with the slope D, but in an opposite way. For example, frequency reduction increases the power generation and decreases the frequency dependent loads. In Fig. 4(b), microgrids also respond to frequency change considering the droop characteristic, D_{MG}. In this figure, $\left(\triangle P_{MG}\right)$ is the change of the microgrid active power consumption at PCC or the response of the microgrid to power system frequency deviations. This response is due to the complementary control of DERs. In Fig. 5, DERs are considered as negative loads and their droop is added to damping ratio of frequency dependent loads. It means that with proper control of DERs in a microgrid, the load-damping constant can be increased.

In steady state conditions, the control mode of DERs should be changed to MPPT and conventional units are responsible for the elimination of the frequency error.

B. Modeling of DERs Dynamic Controller

In this section, a control system is designed to change the equivalent damping coefficient to improve the stability of the system and minimize the frequency deviation. The active power change in power system ($\triangle P_e$) is written by

$$\Delta P_e = \Delta P_L + D\Delta\omega + \Delta P_{MG} \tag{1}$$

where, $\left(\triangle P_{MG}\right)$ is the change in microgrids power consumption given by

$$\Delta P_{MG} = G_{MG}(s)G_c(s)\Delta\omega \tag{2}$$

where, (G_{MG}) is the transfer function of the convertor and (G_c) is the transfer function of the controller. So, the block diagram of the power system for LFC is modified as shown in Fig. 6.

Closed loop transfer function is shown in Fig. 7.

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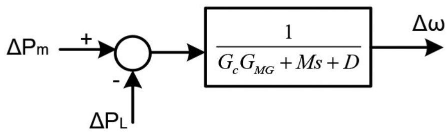

Fig. 7. Closed loop transfer function of system with DER controller.

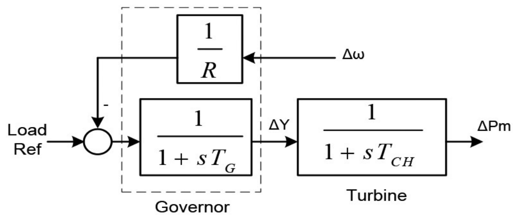

Fig. 8. Transfer function of turbine and governor for reheat steam turbine.

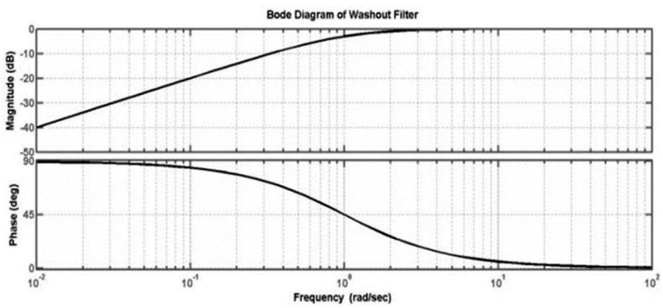

Fig. 9. Frequency response of washout filter.

The transfer function of the turbine and governor is shown in Fig. 8 [2].

The dynamic of the VSC is very fast (time constant is in the range of ms [24], [26]), then its dynamic can be neglected and its transfer function is considered as ($G_{MG} = 1$). So, the controller can be designed to improve the system performance and increase the stability margin. It should be noted that DERs respond to frequency changes just in transients. So, a washout filter is an appropriate solution. The frequency response of the washout filter is shown in Fig. 9.

The proposed method is applied to the power system given in [2]. Its block diagram is modified based on Fig. 6. The closed loop transfer function of the system with and without washout filter is given in (3) and (4), respectively

$$G_{CL} = -\frac{0.003s^2 + 0.025s + 0.05}{0.03s^3 + 0.253s^2 + 0.525s + 1.05} \quad (3)$$

$$G_{CL} = -\frac{0.0003s^3 + 0.0055s^2 + 0.03s + 0.05}{0.003s^4 + 0.0853s^3 + 0.5555s^2 + 1.035s + 1.05}. \quad (4)$$

The frequency deviation after a step change in load is shown in Fig. 10. The proposed control of DERs could decrease frequency deviations significantly.

The root locus (shown in Fig. 11) and bode diagram (presented in Fig. 12) of the compensated system show the improved stability margin and performance.

The performance of the system with the integrator (complementary control) is studied in the following section. As shown in Fig. 13, the frequency deviation is decreased in

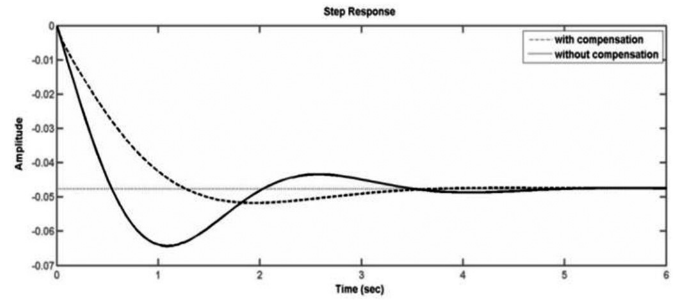

Fig. 10. Frequency deviation after a step change in load.

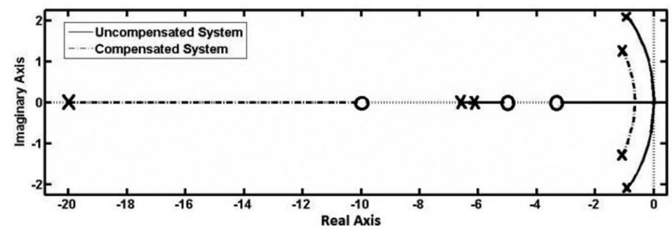

Fig. 11. Root locus of compensated system.

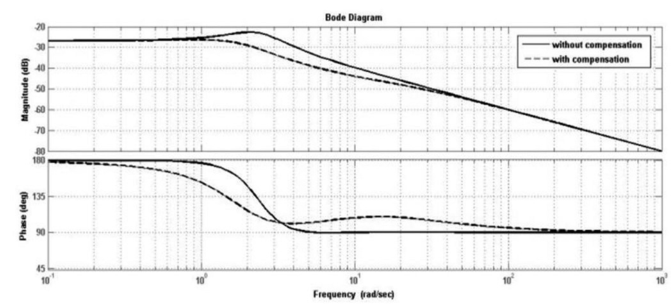

Fig. 12. Bode diagram of compensated system.

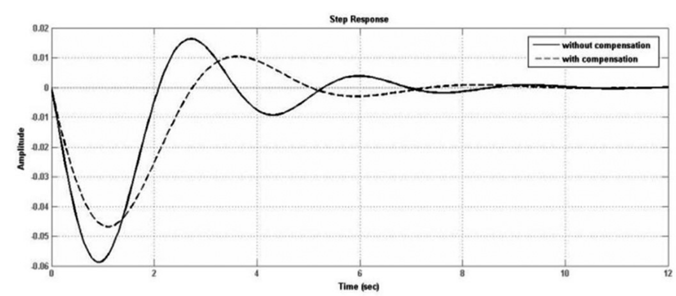

Fig. 13. Frequency deviation in step response.

step response with proposed controller. The performance of the system is similar to uncompensated one in steady state conditions.

The block diagram of two area power system in [2] is modified as shown in Fig. 14.

One term is added to the denominator of the system transfer function. The performance of the controller for two area system is studied. Equation (5) presents the state space presentation of the system with controller

$$\dot{x} = [A_1 \quad A_2 \quad A_3]\, x + Bu + C\dot{u}. \quad (5)$$

Parameters of (5) are presented in the Appendix.

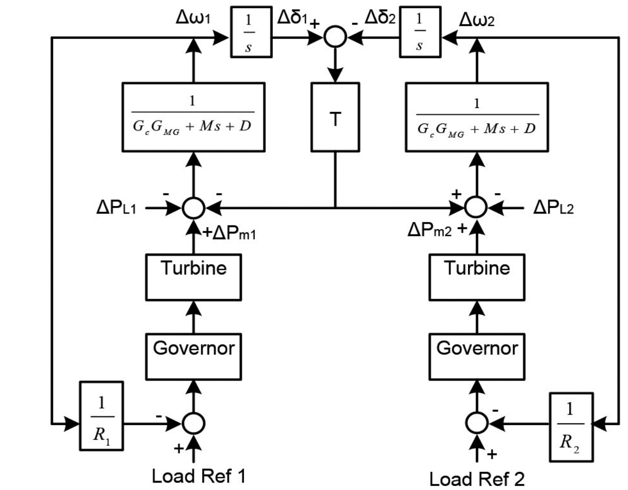

Fig. 14. Block diagram of two area power system.

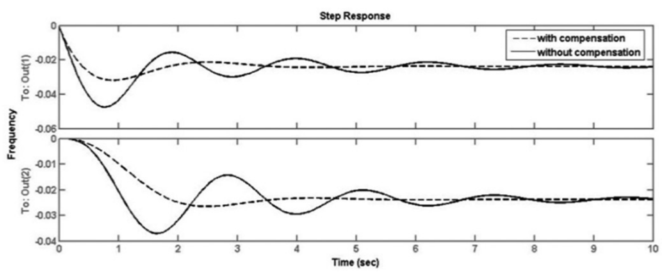

Fig. 15. Frequency deviation in area 1 and 2 after a step power change in area 1.

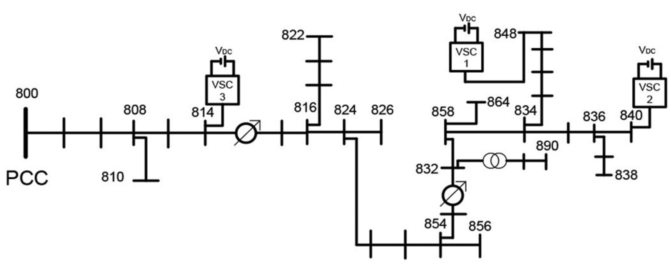

Fig. 16. IEEE 34 bus test feeder.

Fig. 15 shows the frequency deviation in area 1 and 2 after a step load change in area 1.

As it can be seen, the proposed method could improve the stability of two area system significantly.

III. Response of Microgrid to Frequency Deviation

To study the microgrid active power response after a disturbance, a typical microgrid (IEEE 34 Bus distribution system) is simulated in PSCAD/MTDC software as shown in Fig. 16. The load and feeder data are given in [36].

Three DERs are installed at buses 814, 840, and 848. These are connected to the point of coupling (PC) by VSCs. This microgrid should follow the active power reference set by droop characteristic to have the required damping ratio. This droop is defined based on the total generation capacity of the microgrid and acceptable frequency deviation range of the power system.

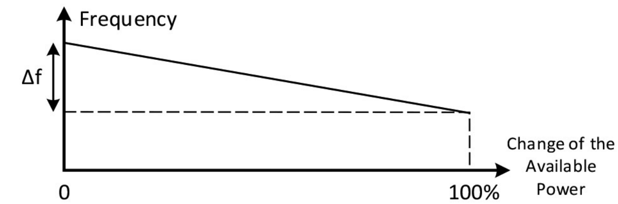

Fig. 17. Frequency droop of microgrid.

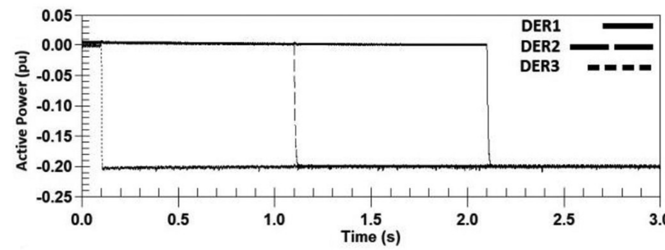

Fig. 18. Power generation of DG 2 after step change in its reference.

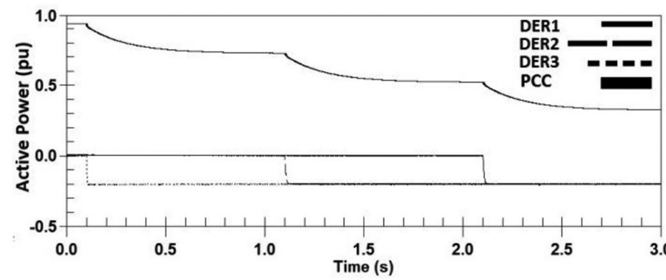

Fig. 19. Active power consumption of microgrid after setpoint change.

For example, 4% droop means that 4% change in the system frequency causes 100% change in the available injected power, as shown in Fig. 17.

It should be noted that because of uncertainty in generation, storage, and loads of the microgrid, the available active power of microgrid is not constant. This uncertainty is due to environmental conditions for renewables (PV and wind generation) and state of charge of battery storage systems. In this section, four control methods are proposed to control the microgrid. The effect of the mentioned uncertainty on the performance of each controller is studied in the next section.

The controller of VSCs is implemented based on Grid Imposed Frequency method in dq frame [26] to decouple active and reactive power control. DER controller should follow the references of active power and PC voltage. Fig. 18 shows the injected active power of DERs to the PC in response to a step change in reference active power (P_{ref}).

Fig. 19 shows the PCC active power after power change of DERs. As it is shown in Fig. 19, the microgrid power is changed with a 200 ms time constant. This time constant is comparable with the mechanical time constant of hydro and steam turbines. This is because of voltage change in system buses after active power injection of DERs.

Fig. 20 shows the voltage change of DER buses after active power change. During transients, injected power of DERs is dissipated in transmission line resistors. As the X/R of distribution lines is not as large as transmission lines, a change in injected active power will affect bus voltages.

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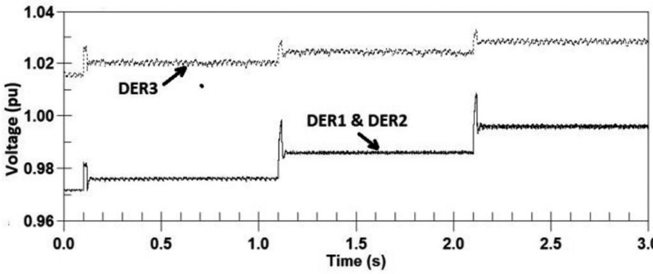

Fig. 20. Voltage change of DER buses.

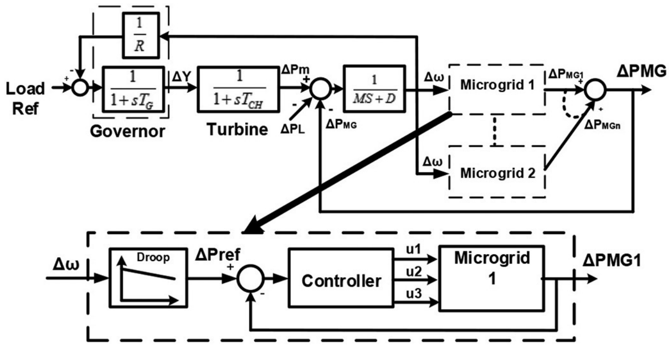

Fig. 21. System with centralized control.

In primary frequency control, rapid response of generation to the frequency deviation is very important for improving the stability of the power system. So, a proper controller can be used to improve the microgrid and power system response. In the following, four control methods are implemented for microgrid DERs.

A. Centralized Control

In the centralized control method, a closed loop control structure is implemented for the microgrid. The control signal is produced based on the difference between microgrid droop characteristic and the PCC active power change. The block diagram is shown in Fig. 21.

In this figure, conventional generators are modeled with equivalent inertia constant (M) and frequency dependent loads are modeled with load damping (D). Conventional generators respond to frequency changes trough their turbine and governor. This is the common dynamic model of the power system for the load-frequency studies [2].

The benefit of the centralized control is that the error signal is based on the injected power at PCC and the implemented closed loop control can minimize the transient error rapidly. It means that with this type of control, the microgrid can follow the droop characteristic with minimum error. The shortcoming of this control method is communication system delays and wide area data acquisition system need.

B. Decentralized Control

1) Simple Decentralized Control: In this method, microgrid is considered as a linear first order system with the transfer function given in

$$G(s) = \frac{1}{1 + 0.2s}. \tag{6}$$

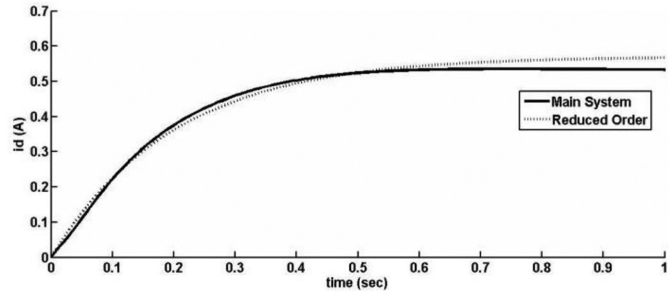

Fig. 22. Step response of the microgrid with exact model and reduced first order model.

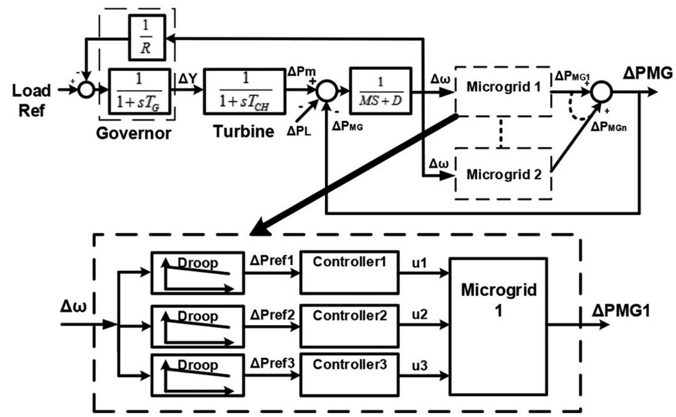

Fig. 23. System with decentralized control.

This model is achieved based on the step response of Fig. 19. To verify this simplified model, linearized dynamic equations of the microgrid are derived in the form of state space equations proposed in [44]. In this model, equivalent balanced three phase microgrid is used [45]. To verify transfer function of (6), step response of this model is shown in Fig. 22. In this figure, active power reference of DERs is the input and injected current at PCC is the output.

To decrease the microgrid time constant in following the droop characteristic, a lag compensator is designed for each DER as

$$G_c(s) = 354.7\frac{1 + 0.13s}{1 + 10s}. \tag{7}$$

VSCs of DERs are equipped with the controller of (7). The output control signal is applied to the VSC active power controller of DERs. The required droop of microgrid is divided among all DERs in the microgrid and output active power of DERs is limited to $\pm 20\%$ of the nominal output power. The block diagram of each control area is shown in Fig. 23.

In the proposed structure, the effect of controlled grid-connected microgrids is added to the system. Assuming fast dynamics for the microgrids, a constant will be added to the load damping in the closed loop form of Fig. 14.

2) Decentralized Control With ANFIS: The centralized controllers can follow the droop characteristic better than decentralized ones but considerable data transfer bandwidth, low reliability, and communication delay are their shortcomings [42]. Decentralized controllers do not need to communicate data, so, after a disturbance, they can act rapidly based on

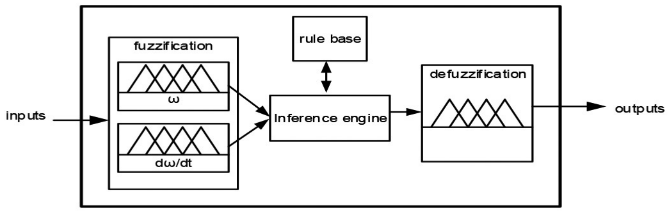

Fig. 24. Structure of fuzzy logic controller.

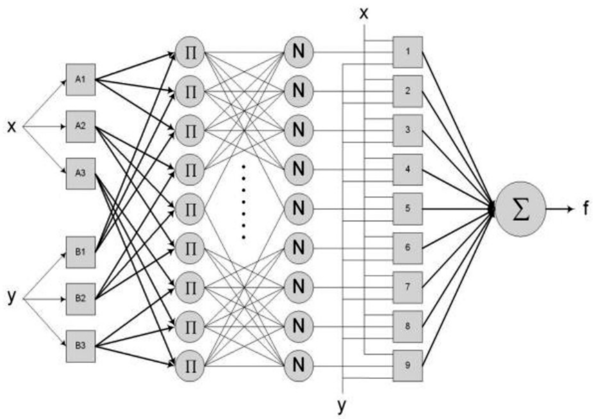

Fig. 25. Structure of ANFIS.

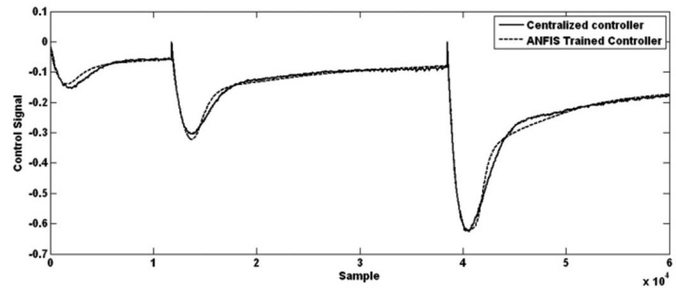

Fig. 26. Training and testing data.

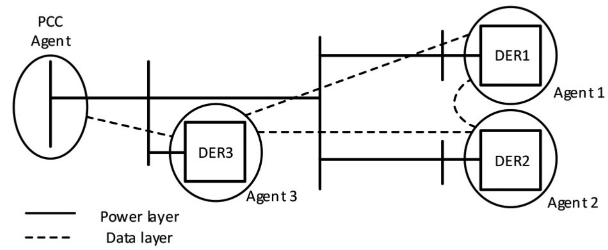

Fig. 27. System with MAS controller.

local measurements, but uncertainty of generation in different conditions may weaken the performance of the system.

In this section, a fuzzy logic controller (FLC) is proposed to overcome the mentioned shortcoming of the decentralized controllers of DERs. The most important benefit of the FLC is considering uncertainty of the system in the controller design [43]. The frequency change and its derivation are inputs to FLCs as shown in Fig. 24.

These controllers are trained by neural network based on the centralized controller behavior of the previous part. Using the derivation of the frequency, the controller can predict the future behavior of the frequency and adjust the output control signal properly. Fig. 25 shows a fuzzy neural network called Adaptive Network Fuzzy Inference System (ANFIS) [37].

Each layer in ANFIS performs a distinct task as follows:

1) computing the matching degree of a variable with fuzzy states;
2) computing the matching degree of a fuzzy state related to different variables;
3) computing the normalized matching degree;
4) computing the consequence of a fuzzy rule inference.

In the learning process, which uses hybrid learning method [38] (combination of back propagation and least square), the function of each node should be differentiable, so the Takagi–Sugeno–Kang (TSK) fuzzy model is used [39]. The frequency change and the centralized controller output are measured after a fault occurrence in three different operating conditions and they are used as training data. Fig. 26 shows training data and output of trained FLC in three different conditions.

C. Multiagent Control

One of the most important shortcomings of DERs, such as wind turbines and photovoltaic systems, is uncertainty in their power generation capability. Also, the state of installed ESSs of DERs is usually unpredictable.

In the previous control methods, each DER controller wants to follow the droop characteristic individually. It means that after a disturbance, some DERs might reach their generation limit while some have not used all of their generation capability. To overcome this problem, the Multiagent System (MAS) can be implemented in the microgrid. In the proposed system, each DER is an agent with measurement and control systems. These agents are vertices of a graph with two layers: 1) power system; and 2) communication layer. In the power system layer, vertices are connected by transmission lines and in the communication layer, vertices are data transfer lines [36]. Each DER is connected to its neighbor agents and the generation and storage capacity can be transmitted through the communication system. MAS based control structure is shown in Fig. 27.

Each DER is equipped with local controller and should follow the microgrid droop characteristic. After a disturbance, the PCC agent sends an activation signal to the agents to change the active output power based on their predefined droop characteristics. When an agent (agent 1) reaches its limit, a signal will be sent to the neighbor agents (agents 2 and 3). These agents decide to change their droop based on the storage and generation capacity and call back agent 1. Agent 1 selects one of them based on the call back signal (capability to change the droop) and sends the activation signal to one of them (for example, agent 2). Agent 2, changes its droop characteristic to compensate the deficiency of agent 1 in the active power supply as shown in Fig. 28.

IV. Simulation Results

The control methods proposed in the previous section are applied to the IEEE 34-Bus microgrid and simulation results

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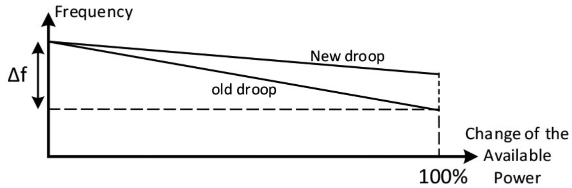

Fig. 28. Change of agent 2 droop when agent 1 reaches its power limit.

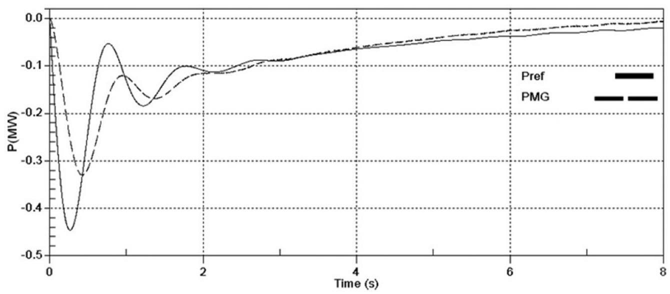

Fig. 29. Microgrid power at PCC and its reference for decentralized control.

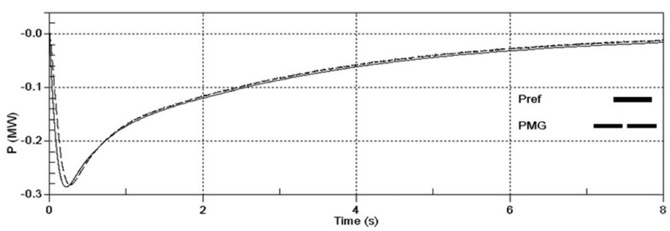

Fig. 30. Microgrid power at PCC and its reference for centralized control.

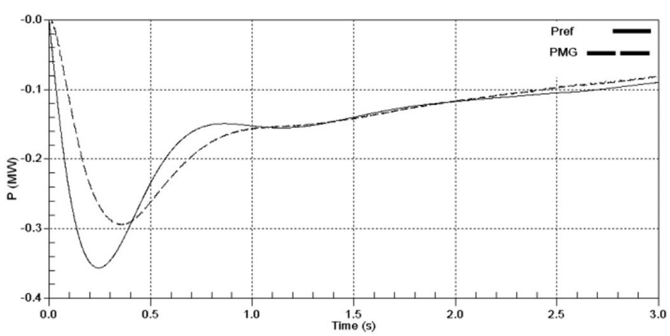

Fig. 31. Microgrid power at PCC and its reference for ANFIS.

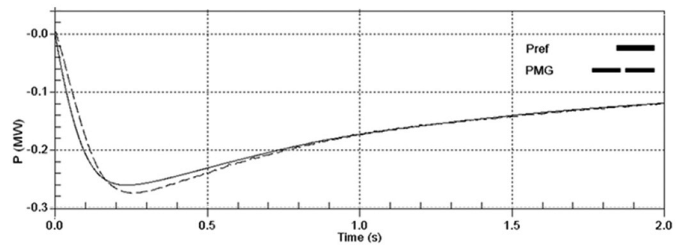

Fig. 32. Microgrid power at PCC and its reference for MAS control.

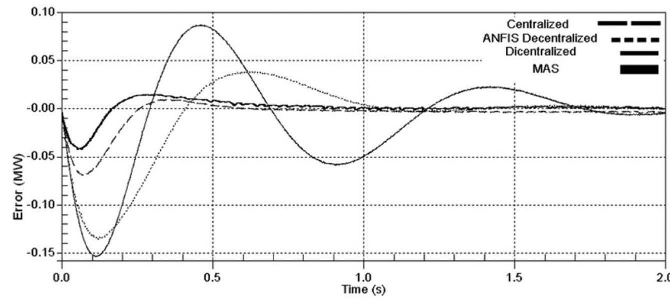

Fig. 33. Control errors for proposed control methods (similar generation).

TABLE I
GENERATION LIMIT OF DERS

	Generation Limit(pu)
DER1	±0.1
DER2	±0.2
DER3	±0.3

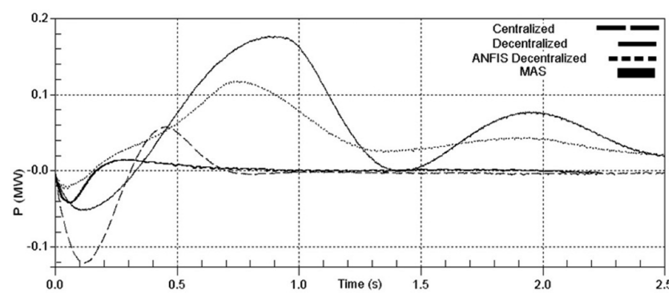

Fig. 34. Control errors for proposed control methods (different generation).

are presented in this section. It is assumed that penetration of DERs in the power system generation capacity is 0.3 pu.

A. Simplified Model of the Power System With Coherent Generation

Two different operating conditions are considered for microgrid.

1) *DERs With Similar Generation and Storage Capability:* Figs. 29–32 show the microgrid power reference (P_{ref}) defined by droop characteristic and micrigrid power change at PCC (P_{MG}) after a step change of 0.1 pu in the power system load active power. The output power of DERs is limited to ±0.2 pu based on the microgrid rated power. The control errors (difference between microgrid power at PCC and its reference) are shown in Fig. 33. It is shown that MAS controller could follow the droop characteristic with minimum error. It should be noted that communication delays are considered in data transfer of agents based on the smart grid communication system presented in [46].
2) *DERs With Different Generation and Storage Capability:* In this operating condition, the output power limits of DERs are different as listed in Table I.

The control errors (difference between microgrid power at PCC and its reference) are shown in Fig. 34. It is shown that MAS controller could follow the droop characteristic like previous section and it is not sensitive to the difference of the generation capability of DERs.

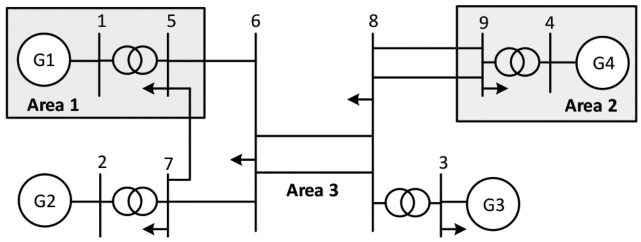

Fig. 35. IEEE 9-Bus single line diagram.

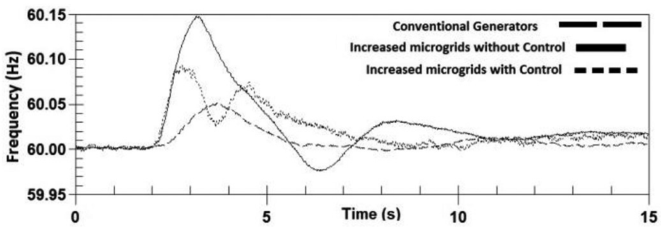

Fig. 36. System frequency after disturbance (three conditions).

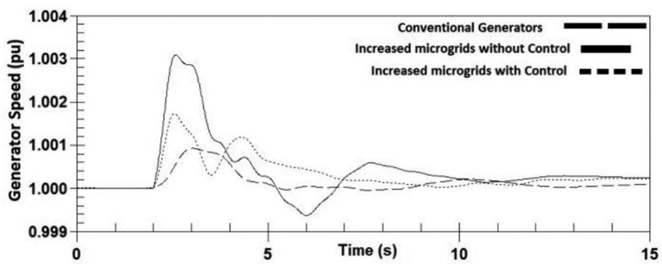

Fig. 37. Speed of generator 1 after disturbance (three conditions).

B. Multimachine Power System

The single line diagram of IEEE 4-machine, 9-bus power system [46] is shown in Fig. 35. Generators 1 and 4 are aggregated models of the synchronous generators of areas 1 and 4, respectively. Also, loads of areas 1 and 2 are aggregated at buses 5 and 9, respectively. Generators 2 and 3 with the reminding loads and transmission lines and transformers form area 1. The exact model of the system including synchronous generators, automatic voltage regulators (AVRs), power system stabilizers (PSSs) transformers, transmission lines, and loads are implemented in the PSCAD software. The frequency dependent model [2] is used for the power system loads as presented in

$$P = \left(\frac{V}{V_0}\right)^{K_v} \left(1 + K_p \triangle f\right) \tag{8}$$

where V_0 is the nominal voltage of the load bus, K_v and K_p are the dP/dV and dP/df indexes of active power, respectively.

This system is modified to satisfy the assumptions of the paper. The inertia constant (H) and generation capacity of the synchronous generators are reduced to 70% of the nominal values and the inverter based microgrids are installed beside loads to compensate the reduced capacity. The MAS control method proposed in Section III is used to control the microgrids. To study the performance of the proposed controller, a disturbance occurs as 2% load interruption.

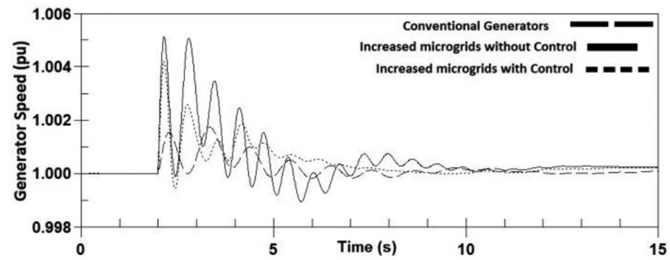

Fig. 38. Speed of generator 2 after disturbance (three conditions).

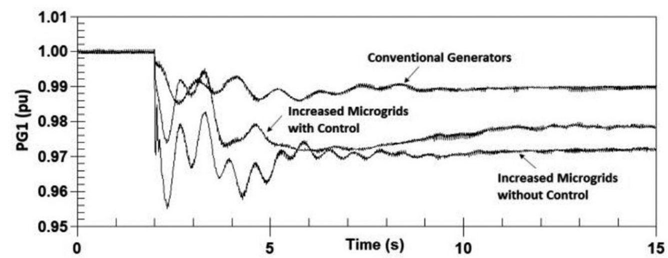

Fig. 39. Active power of generator 1 after disturbance (three conditions).

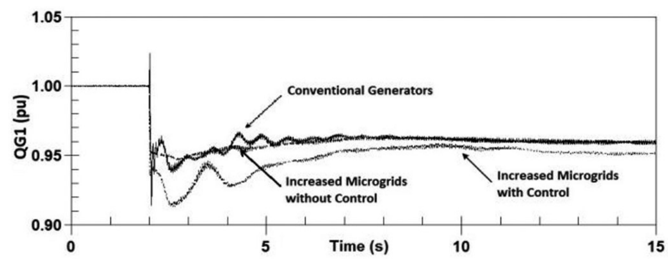

Fig. 40. Reactive power of generator 1 after disturbance (three conditions).

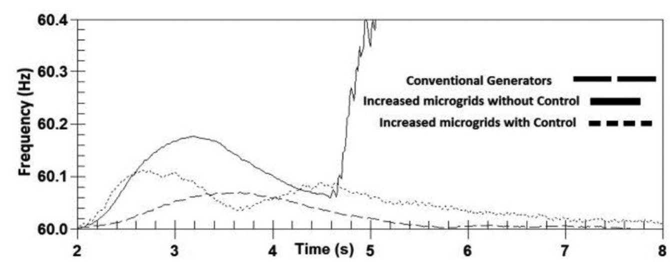

Fig. 41. System frequency after disturbance for three conditions.

Fig. 36 shows the system frequency after the disturbance for three conditions:

1) conventional system with synchronous generators;
2) increased penetration of microgrids to 30% without contribution to the frequency control; and
3) increased penetration of microgrids to 30% with contribution to the frequency control.

Active and reactive power of generator 1 is shown in Figs. 39 and 40, respectively.

As it is shown in Fig. 36, contribution of microgrids to the frequency control of the power system could improve the primary frequency control significantly. Without this contribution, frequency deviation increases due to the reduced inertia of the system.

The speeds of generators 1 and 2 are shown in Figs. 37 and 38, respectively. Increased penetration of microgrids causes unacceptable oscillations of frequency that cannot be damped considerably by PSSs. It means that stability margin of the system is decreased due to the decreased inertia constant. Injecting the active power proportional to the frequency (generators speed) can damp the frequency oscillations, like the power produced by PSSs.

To show the importance of the proposed method, a larger disturbance as 4% load interruption is occurred in the system and the frequency of the system is shown in Fig. 41. It can be seen that high penetration of microgrids makes the system unstable after the disturbance. Also, proper control of microgrids could improve stability of the system.

V. Conclusion

In this paper, the effect of high penetration of DERs on power system frequency control has been studied. Using the advantage of the VSC fast dynamic, the injected active power of DERs can change rapidly. So they can be used to improve the primary frequency control. Microgrids are responsible to follow the active power determined by the frequency droop characteristic of power system. They can be considered as extra damping in the power system load. Four control methods have been proposed to control DERs in the microgrid. These methods have been applied to a sample microgrid (IEEE-34Bus) and simulation results have been studied. It is shown that the best method to follow the droop characteristic is the MAS control system. Also, the proposed control method is implemented on the 9-bus power system in PSCAD software. Simulation results show the effectiveness of the proposed method to improve the power system stability.

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Appendix

$$x = \begin{bmatrix} \Delta\delta_1 \\ \Delta\delta_2 \\ \Delta\omega_1 \\ \Delta\omega_2 \\ \Delta P_{m1} \\ \Delta P_{m2} \\ \Delta Y_1 \\ \Delta Y_2 \\ x_9 \\ x_{10} \end{bmatrix} \quad u = \begin{bmatrix} \Delta P_{L1} \\ \Delta P_{L2} \end{bmatrix} \quad A_1 = \begin{bmatrix} & 0 & 0 & 1 & 0 & \\ & 0 & 0 & 0 & 1 & \\ 0 & \cdots & (2\times 2) & \cdots & & 0 \\ & 0 & 0 & -\frac{1}{R_1 T_{G1}} & 0 & \\ & 0 & 0 & 0 & -\frac{1}{R_2 T_{G2}} & \\ & -\frac{T}{M_1 T_{W1}} & \frac{T}{M_1 T_{W1}} & -\frac{1}{M_1}\left(T - \frac{D_1}{T_{W1}}\right) & \frac{T}{M_1} & \\ & \frac{T}{M_2 T_{W2}} & -\frac{T}{M_2 T_{W2}} & \frac{T}{M_2} & -\frac{1}{M_2}\left(T - \frac{D_2}{T_{W2}}\right) & \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0 & \cdots & (4\times 4) & \cdots & 0 \\ -\frac{1}{T_{CH1}} & 0 & -\frac{1}{T_{CH1}} & 0 & \\ 0 & -\frac{1}{T_{CH2}} & 0 & -\frac{1}{T_{CH2}} & \\ 0 & 0 & -\frac{1}{R_1 T_{G1}} & 0 & \\ 0 & 0 & 0 & -\frac{1}{R_2 T_{G2}} & \\ \frac{1}{M_1}\left(\frac{1}{T_{W1}} - \frac{1}{T_{CH1}}\right) & 0 & \frac{1}{M_1 T_{CH1}} & 0 & \\ 0 & \frac{1}{M_2}\left(\frac{1}{T_{W2}} - \frac{1}{T_{CH2}}\right) & 0 & \frac{1}{M_2 T_{CH2}} & \end{bmatrix} \quad B_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -\frac{1}{M_1 T_{W1}} & 0 \\ 0 & -\frac{1}{M_2 T_{W2}} \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 0 & \cdots & (2\times 2) & \cdots & 0 \\ 1 & & & & 0 \\ 0 & & & & 1 \\ 0 & \cdots & (4\times 2) & \cdots & 0 \\ -\frac{(K_{W1}+M_1+D_1 T_{W1})}{M_1 T_{W1}} & & 0 & & \\ 0 & & -\frac{(K_{W2}+M_2+D_2 T_{W2})}{M_2 T_{W2}} & & \end{bmatrix} \quad B_2 = \begin{bmatrix} 0 & \cdots & (8\times 2) & \cdots & 0 \\ -\frac{1}{M_1} & & & & 0 \\ 0 & & & & -\frac{1}{M_2} \end{bmatrix}.$$

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