Wide-Area Stabilizing Control using Distributed Generation Systems

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***Abstract* – This paper presents a wide-area control strategy to stabilize power systems using Distributed Generation (DG) sources. The proposed control strategy improves the first-swing stability of power systems subjected to large disturbances. The proposed strategy is based on energy function and implements a kinetic energy-based control algorithm applied to Solar Photovoltaic (PV) and Battery Energy Storage Systems (BESS) in distribution grids. The presented approach relies on the application of a Kalman filter and Phasor Measurement Units (PMU) to estimate the inter-area dynamics of the system in terms of angles and velocities based on a reduced aggregated system model. The performance of the proposed control strategy is evaluated on Kundur's two-area four-machine test system and obtained results show significant improvements in system post-fault stability when the proposed control strategy is applied.**

***Index Terms* — Wide-area Control, Phasor Measurement Unit, Distributed Generation Systems**

I. INTRODUCTION

Wide-area monitoring and control systems have transformed the way modern power systems are managed and operated. The advancements in networking and telecommunication technologies coupled with capable monitoring and measurement equipment, notably synchronized Phasor Measurement Units (PMU) have provided system operators with the necessary tools and a framework for real-time monitoring and control of large-scale power networks over long distances [1, 2]. The increase in demand for electricity has stressed existing transmission infrastructures, pushing them to their limits and making them more vulnerable to disturbances. Limited investment in new power generation and transmission infrastructure due to cost and environmental factors has exacerbated the issue. As a result, systems operators have faced many challenges to meet the increasing demand while maintaining the reliability and resilience of their power networks [3-5]. To tackle these challenges, systems operators have developed many applications and methods based on wide-area monitoring and control systems, utilizing controllable devices such as Flexible AC Transmission systems (FACTS), namely Static VAR Compensators (SVC) [6-8], allowing them to improve system operating conditions and mitigate possible contingencies.

Over the recent years, distributed generation (DG) systems have grown in popularity. Among DG systems, Solar Photovoltaic (PV) and Battery Energy Storage Systems (BESS) have been installed in increasing numbers at distribution level networks due to factors such as increasing electricity prices and government incentives to encourage the transition to cleaner renewable energy sources. Besides power generation and storage, DG systems have been used to provide a range of ancillary services in the form of active and reactive power compensation to improve grid operating conditions. These services can also be provided to power transmission networks due to the interconnectivity between transmission and distribution grid by grouping and controlling a large number of DG systems, allowing them to manipulate transmission system operating conditions [9-11].

Distributed generation (DG) sources are nowadays installed in large numbers across many power networks over large geographical areas, forming scattered groups that are often locally managed and controlled [12]. Controlling the operation of groups of DG systems across a large-scale power network is a task that can be performed remotely by combining Smart Grid (SG) communication network (SGCN) and control infrastructure with wide-area monitoring control systems, allowing to integrate DG systems in wide-area control applications. This provides a hierarchical control structure and the opportunity to develop wide-area stabilizing control strategies by tapping into the bulk ancillary services that can be obtained from a large number of DG systems placed across a large-scale power network. This paper aims to propose such a method for improving power system stability. To achieve this objective, a wide-area stabilization control algorithm based on energy function for improving first swing stability is proposed and applied using groups of DG systems comprised of PV and BESS. The energy function-based wide-area control approach implements a nonlinear wide-area control strategy and relies on remote PMU measurement and estimations of aggregated system equivalent area dynamics, specifically angles and velocities by employing a nonlinear Kalman filtering approach [13, 14]. The performance of the proposed wide-area control approach is evaluated on the two-area four-machine test system by Kundur, showing the feasibility of the proposed approach.

The remaining parts of this paper are organized as follows: Section II describes the concept of wide-area stabilizing control using DG systems. In section III, the energy function-based wide-area control strategy is presented. In section IV, the first swing stabilization control criteria is defined. In section V, the wide-area control method is applied to the test system through simulation. The conclusion is given in section VI.

II. WIDE-AREA STABILIZING CONTROL USING DISTRIBUTED GENERATION (DG) SYSTEMS

Developing wide-area control strategies using Distributed Generation (DG) systems relies on the existence of a large number of DG systems in distribution networks. In the present era, the growing popularity of DG sources has led to the installation of a large number of PV and BESS systems in distribution grids serving as local generators and energy storage systems. A block diagram representing a grid-connected DG system comprised of PV and BESS with a load is shown in Fig. 1.

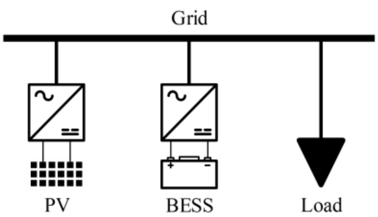

Fig. 1. Block diagram of a Distributed Generation (DG) system

A large number of PV and BESS systems in distribution grids can provide significant power generation and storage capability and facilitate a range of ancillary services through supplying or absorbing additional active or reactive power to and from the distribution grid. Due to the interconnectivity between power transmission and distribution networks, power can flow bidirectionally and the operation of DG systems can propagate and impact the stability and operation of the entire transmission system. This means that groups of DG systems in distribution grids can have a stabilizing effect by injecting or absorbing active or reactive power from the transmission network when required, allowing to enhancing system stability and operation. To better demonstrate this concept, it is essential to focus on a distribution grid comprised of many DG systems connected to the transmission system (External Grid) through a transformer and a transmission line, as illustrated in Fig. 2.

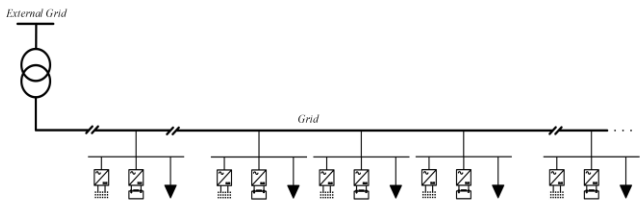

Fig. 2. Distribution power grids

The concept behind this approach is that the flow and exchange of power between a power transmission network and distribution grids can be manipulated by controlling and coordinating the operation of DG systems inside distribution grids. This provides the capability to affect the balance of power and energy in the system, allowing to mitigate system disturbances using PV and BESS systems in distribution grids by injecting or absorbing power from the transmission network. In this scenario, PV systems operate as generators, injecting power into the distribution grid, while BESS systems operate as both generators and energy storage systems.

The effective utilization of DG systems for this purpose relies on the presence of a capable control and monitoring infrastructure, which is nowadays provided by Smart-Grid (SG) communication network (SGCN) and control systems in distribution grids. This infrastructure can be combined with wide-area monitoring and control systems to develop a hierarchical control structure. In this case, the wide-area monitoring and control system operates as the high-level control in this hierarchy, supervising the operation of the transmission system and issuing control commands to DG systems via the SG control infrastructure. The SG infrastructure functions as the lower-level control layer, managing the operation of DG systems within distribution grids and facilitating communication with the higher-level wide-area monitoring and control system to enable the implementation of wide-area control strategies. This concept is shown graphically in Fig. 3, representing the relation between wide-area monitoring and control systems and DG systems controlled via the Smart Grid (SG).

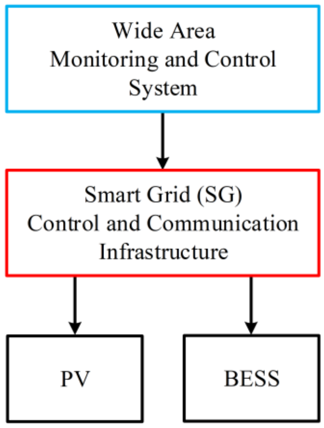

Fig. 3 Hierarchical control structure

III. WIDE-AREA STABILIZING CONTROL OF POWER SYSTEMS BASED ON ENERGY FUNCTION

The Lyapunov Energy function is a widely used tool for power systems stability assessment and design of stabilizing control strategies. Based on the Lyapunov theorem, the stability of a power system can be determined by analyzing the transient energy of the system at the point of fault clearing. This transient energy is responsible for causing synchronous generators to swing away from the equilibrium point of operation. During a transient event, the system accumulates excess transient energy that is converted to kinetic energy, which the system must absorb and dissipate to maintain stability [14-17]. In power system applications, the candidate Lyapunov function is derived from the total transient energy of the system which is the sum of kinetic and potential energies of the system and for an m machine power system can be expressed as [15]:

$$V(\delta,\omega) = V_{KE}(\omega) + V_{PE}(\delta) \tag{1}$$

$$V(\delta,\omega) = \frac{1}{2}\sum_{i=1}^{m} M_i\, \omega_i^2 - \sum_{i=1}^{m} \int_{\delta_i^s}^{\delta_i} f_i(\delta)\, d\delta_i \tag{2}$$

where V is the total transient energy, V_{KE} and V_{PE} are kinetic and potential energies of the system. M is machine inertia, δ and ω are the machine angle and velocity in the center of inertia (COI) reference frame and f is a function describing the model of the system. The objective of designing wide-area controllers based on kinetic energy is to achieve a negative rate of change of kinetic energy or $(-\dot{V}_{KE})$ in order to dissipate the excess kinetic energy of the system and keep the system stable. Hence, the derivative of the system kinetic energy can be expressed as:

$$\dot{V}_{KE} = \sum_{i=1}^{n} M_i \dot{\delta}_i \ddot{\delta}_i \tag{3}$$

The kinetic energy-based wide-area controllers are designed to enhance the stability of the system by maximizing the reduction rate of kinetic energy to accelerate the absorption and dissipation of excess kinetic energy and can be applied to controllable devices to achieve a good nonlinear stabilization performance [16, 18]. Implementation of kinetic energy-based control for stabilization of large initial angle swings (first swing) and damping modes require different control actions to stabilize the system. Based on [6] and [7], large-disturbance stability can be assessed and enhanced based on the transient energy of critical machine groups or areas in immediate danger of separation. Therefore, the large angle swing (first swing) stabilization is designed to maximize the reduction rate of the kinetic energy of coherent machine groups or aggregated areas connected through weak links or interconnects. After large angle swings are passed, the wide-area controller switches to damping mode to address subsequent inter-area oscillatory modes by maximizing the reduction rate of the total kinetic energy of the entire system [14, 18]. The control action of the wide-area controller can be summarized as follows:

$$u = \begin{cases} U_{FS}(V_{KE}^{Cr}) & \vartheta_{FS} \\ U_D(V_{KE}^{T}) & \vartheta_D \end{cases} \tag{4}$$

where u is the wide-area controller, U_{FS} and U_D are functions describing first swing and damping control actions and ϑ_{FS} and ϑ_D describe the criteria for the first swing and damping control modes, respectively. The wide-area controller switches between the first swing and damping modes according to criteria defined by ϑ_{FS} and ϑ_D based on equivalent system inter-area dynamics, specifically angles and velocities of aggregated systems areas. Obtaining the equivalent system inter-area dynamics relies on the estimation of a reduced system aggregate model through identifying coherent generator groups that can be aggregated into dynamic equivalents, allowing the inter-area dynamics of the system to be represented by a set of simplified equivalent machines and interconnections as demonstrated in [19]. The estimation of reduced equivalent aggregate model parameters is accomplished through the online processing of data acquired by PMUs that are strategically positioned throughout the system to be more sensitive to inter-area system dynamics while minimizing their sensitivity to local system modes. Due to the nonlinear behavior of post-fault power systems, to minimize the effect of local system modes on the estimation of inter-area system dynamics, the nonlinear Kalman filtering approach presented in [13, 14] is employed. The Kalman filter estimates the equivalent aggregated system area angles and velocities that represent the inter-area interactions of the system, which can be described by a set of nonlinear differential-algebraic equations (DAE):

$$\begin{cases} \dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}) \\ \boldsymbol{y} = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{u}) \end{cases} \tag{5}$$

where the state vector $\boldsymbol{x}$ contains angles and velocities of aggregated areas represented by the classical machine model, the vector $\boldsymbol{u}$ contains control inputs, and the output vector $\boldsymbol{y}$ contains PMU measurements. The nonlinear Kalman Filter can be summarized as:

$$\bar{x}_k = f_d(\hat{x}_{k-1}, u_{k-1}) \tag{6}$$

$$\bar{y}_k = H\bar{x}_k \tag{7}$$

$$\hat{x}_k = f_d(\hat{x}_{k-1}, u_{k-1}) + L_k(y_k - \bar{y}_k) \tag{8}$$

where $\bar{x}_k$ and $\hat{x}_k$ are predicted and updated system states, $\bar{y}_k$ is the vector of measurements obtained by PMUs, H represents the relationship between the predicted states and PMU measurements, L_k is the Kalman filter gain and f_d is the discretized nonlinear swing equation of the identified reduced aggregated system model. The nonlinear Kalman filter provides instantaneous estimations of equivalent area angles and velocities of the reduced aggregated system model to ensure the feasibility of real-time application of the wide-area control method [20].

IV. FIRST-SWING STABILITY USING DISTRIBUTED GENERATION (DG) SYSTEMS

Implementing a wide-area first swing stabilizing control using (DG) systems located in distribution grids can improve the post-fault transient stability of a power system subjected to a disturbing event. In this scenario, groups or clusters of DG systems comprised of PV and BESS systems are used as controllable devices that can provide ancillary services, specifically active and reactive power compensation, in order to effect and manipulate grid conditions. Due to the interconnectivity between power transmission networks and distribution grids, any compensatory action provided by DG systems in distribution grids can propagate to the transmission network given the bidirectional nature of power flow, resulting in a direct effect on system operation and stability conditions. This can directly affect the power exchange between the transmission network and distribution grids, which directly manipulates the level of loading imposed by distribution grids on the transmission network. The manipulation of system loading allows to dissipate the excess system kinetic energy accumulated during the transient event, resulting in the restoration of normal operating conditions and the preservation of system stability. Essentially, the level of loading imposed on the transmission network by distribution grids is increased in areas with excess levels of kinetic energy (Accelerating Area) and decreased in areas with a deficit (Decelerating Area), allowing the system to reach energy balance and maintain stability. The stability characteristics of the system are obtained through the application of PMUs and the nonlinear Kalman filtering approach illustrated in [13, 14], utilizing wide-area monitoring and control systems to estimate equivalent inter-area dynamics of the system in terms of area angles and velocities which can be used to detect acceleration and deceleration of system areas. On this basis, the wide-area first swing stabilizing control action can be implemented by channelling the wide-area control command through Smart Grid (SG) communication and control infrastructure to PV and BESS systems, managing and controlling their operation according to the following wide-area stabilizing control action:

$$u_{PV} = \begin{cases} switch\ off\ \ \dot{\delta}_n > 0\ \ and\ \ \delta_n > \eta\ (Accelerating) \\ switch\ off\ \ \dot{\delta}_n > 0\ \ and\ \ \delta_n < \eta\ (Decelerating) \\ \quad switch\ on \quad Otherwise \end{cases} \tag{9}$$

$$u_{BESS} = \begin{cases} -1\ \ \dot{\delta}_n > 0\ \ and\ \ \delta_n > \eta\ (Accelerating) \\ \ \ 1\ \ \dot{\delta}_n < 0\ \ and\ \ \delta_n < \eta\ (Decelerating) \\ \ \ switch\ off\ \ \ Otherwise \end{cases} \tag{10}$$

where u_{PV} is the wide-area control criteria for solar PV systems, u_{BESS} represent the wide-area control criteria for BESS, $\delta_n$is the equivalent angle of area n and η represents the equivalent area angle threshold which is a set distance from the critical clearing angle. The wide-area controller detects whether an area is accelerating or decelerating during the initial large-angle swing (First Swing). PV systems are switched off during the acceleration phase of the initial area angle swing once the area angle threshold is reached, preventing PVs from providing the system with any extra active power and accommodating faster dissipation of the excess system transient energy. BESS systems are controlled to absorb active power during the area acceleration phase and inject active power back into the system during deceleration to limit power fluctuations and successive large-angle swings. The block diagram representation of the wide-area controller is shown in Fig. 4 below:

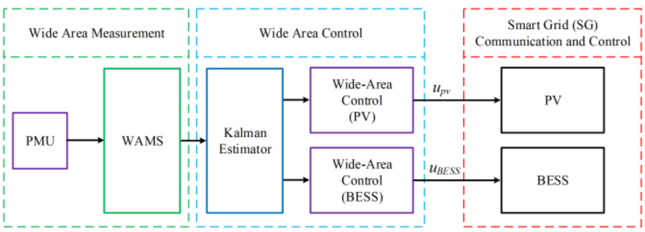

Fig. 4. Wide-Area Controller using DG systems

V. SIMULATION STUDY

In order to evaluate the performance of the proposed wide-area first-swing stabilization control strategy, it was applied to Kundur's two area four machine test system in the DIgSILENT Power Factory simulation software package. The test system was modified by placing five DG groups at system load buses 7 and 9, which are area interconnect buses as shown in Fig. 5. The total combined power generation capacity of PV and BESS systems in DG groups located at each bus was chosen to be 10% PV and 10% BESS along with a 5% extra load relative to the total default load at the bus. Inside each DG group, a combination of five PVs, five BESS and five loads are placed. It is assumed that in nominal operating conditions, PVs operate at half capacity and feed the 5% extra load, and BESS systems are on standby.

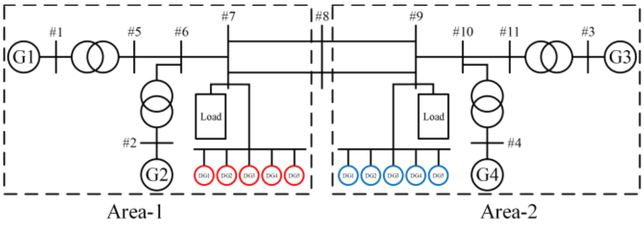

Fig. 5. Two area four machine system with groups of DG systems

A. Uncontrolled system

To provide a criterion for comparison, the test system with DG groups was simulated without wide-area control. A three-phase short-circuit fault was applied on bus 8, which is the mid-point on the transmission lines connecting the two areas of the system. In the performed simulation, the fault duration was set to 664 ms equivalent to the critical clearing time (CCT) of the system. To show the stability characteristics of the uncontrolled system, graphs of generator rotor angles in the Center of Inertia (COI) reference frame are shown in Fig. 6. Graphs of the active and reactive power of loads and DG group bus voltages in both areas of the system are shown in Fig. 7, 8 and 9, respectively.

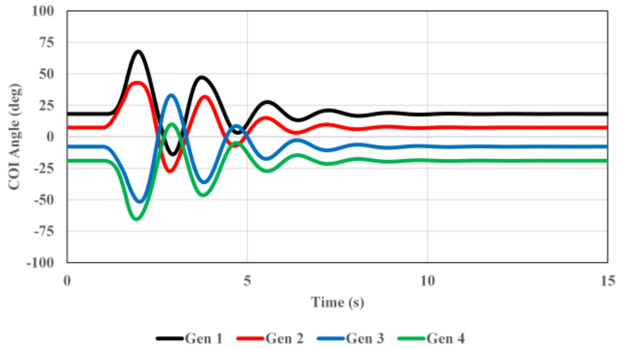

Fig. 6. Generator rotor angles in the COI reference frame (Uncontrolled)

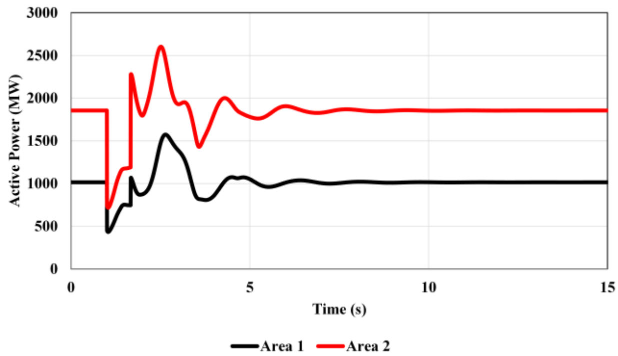

Fig. 7. Active power of loads (Uncontrolled)

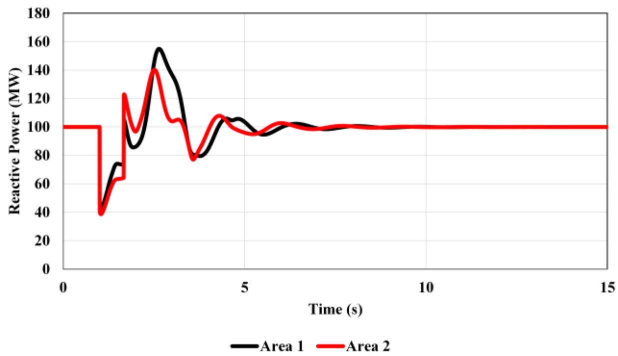

Fig. 8. Reactive power of loads (Uncontrolled)

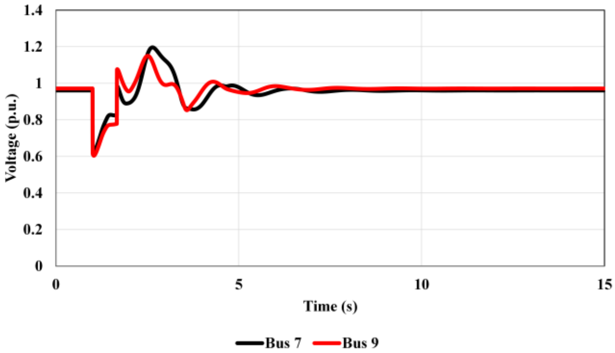

Fig. 9. Load / DG cluster bus voltage (Uncontrolled)

B. *Controlled system*

The wide-area control method was applied to the test system. Similar to the uncontrolled systems, the same three-phased short-circuit fault was applied on bus 8, with a duration of 664 ms, equal to the uncontrolled system's CCT. The first swing wide-area control criteria represented in (9) and (10) are applied to DG systems in both system areas. To show the stability characteristics of the controlled system, graph of generator rotor angles in the Center of Inertia (COI) reference frame are shown in Fig 10, demonstrating the performance of the wide-area control method in improving the first-swing stability of the system. The CCT of the system was increased to 1033 ms, which is a 55.57% improvement compared to the uncontrolled systems. Power outputs of PVs and BESS systems are shown in Fig. 11, 12, 13, and 14. The active and reactive power of loads and DG group bus voltages in both system areas are shown in Fig. 15, 16 and 17, respectively.

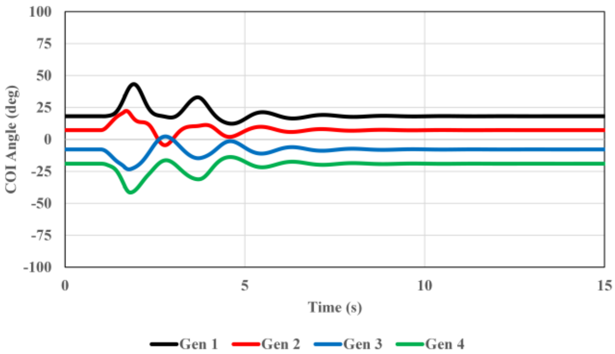

Fig. 10. Generator rotor angles in the COI reference frame (Controlled)

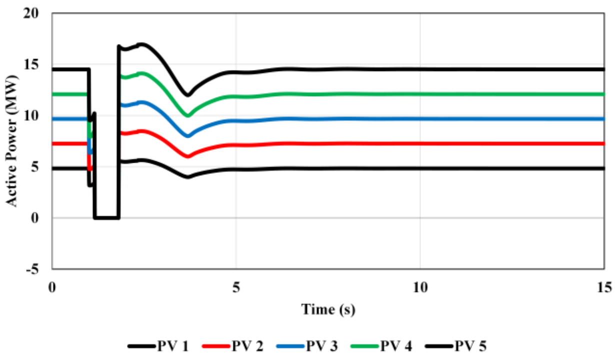

Fig. 11. Active power outputs of PVs in area 1 (Controlled)

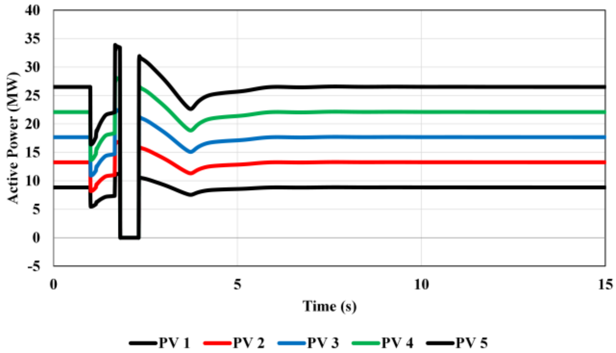

Fig. 12. Active power outputs of PVs in area 2 (Controlled)

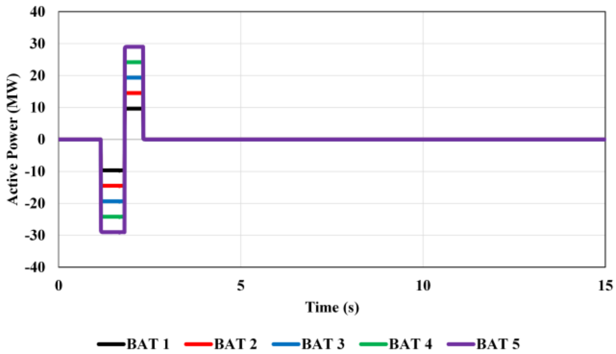

Fig. 13. Active power outputs of BESS in area 1 (Controlled)

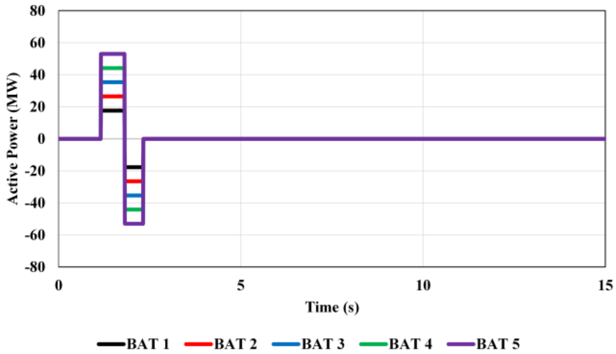

Fig. 14. Active power outputs of BESS in area 2 (Controlled)

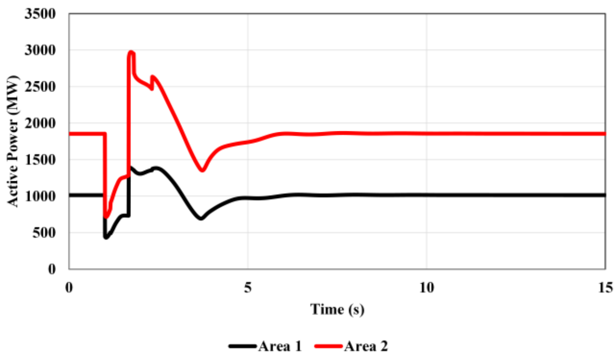

Fig. 15. Active power of loads (Controlled)

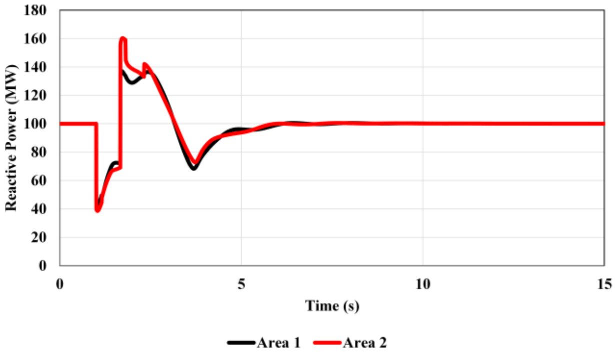

Fig. 16. Reactive power of loads (Controlled)

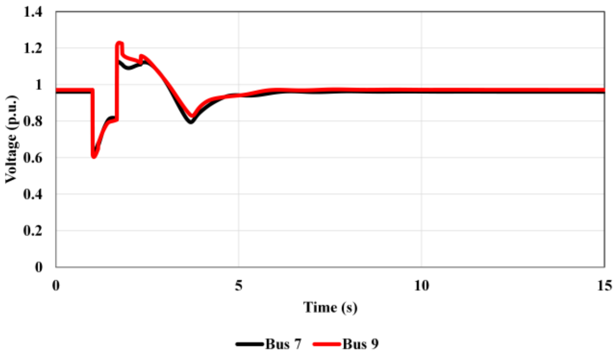

Fig. 17. Load / DG cluster bus voltage (Controlled)

VI. CONCLUSION

In conclusion, this paper has proposed a wide-area control strategy to enhance the first swing stability of power systems subjected to large disturbance using Distributed Generation (DG) systems. The proposed wide-area control approach is a kinetic energy-based control strategy that relies on the application of a Kalman filter and Phasor Measurement Units (PMU) for estimation of equivalent inter-area dynamics of the system in terms of angles and velocities for control implementation. The proposed approach constructs a hierarchical control framework by combining control capabilities of wide-area monitoring and control systems and Smart Grid (SG) communication network (SGCN) and control infrastructure allowing to integrate and utilize DG systems in wide-area control applications such as wide-area stabilizing control strategies. The proposed approach was applied to Kundur's two-area four-machine test system, and the results demonstrate significant improvements in system stability following a large disturbance. The proposed approach can be extended to large scale power networks and has the potential to offer an effective and practical solution for stabilizing power systems with large number of DG systems.

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