Virtual Generators: Simplified Online Power System Representations for Wide-Area Damping Control

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***Abstract*—This paper introduces a new concept called a Virtual Generator (VG). VGs are simplified representations of groups of coherent synchronous generators in a power system. They resemble commonly used power system dynamic equivalents obtained via generator aggregation techniques. Traditionally power system dynamic equivalents are developed offline, fixed, and used to replace large portions of the system that are considered external to the portion of the system being analyzed in detail. In contrast, VGs are calculated online, are not limited to representing external areas of the system being analyzed/controlled, and do not replace any portion of the power system. Instead, they allow wide-area damping controllers (WADCs) to exploit the realization that a group of coherent synchronous generators in a power system can be controlled as a single generating unit for achieving wide-area damping control objectives. The implementation of VGs is made possible by the availability of Wide-Area Measurements (WAMs) from Phasor Measurement Units (PMUs). To the authors' knowledge, this is the first time that the use of power system equivalencing techniques has been extended to real-time WADC. Simulation studies carried out on the 68-bus New England/New York power system demonstrate that intelligent controllers developed using VGs can significantly improve the stability of a power system by effectively damping low-frequency interarea oscillations.**

Keywords-virtual generator; power system stabilizer; wide-area control; power system equivalents; intelligent control; approximate dynamic programming; adaptive critic designs; generator coherency; interarea oscillations

I. Introduction

Power systems are being pushed to operate closer to their stability limits. This trend is caused by increasing electrical energy demands coupled with limited investment in transmission infrastructure and energy market deregulation. One of the manifestations of this stability reduction is the emergence of low-frequency interarea oscillations. Some power systems report a noticeable increase in the number of events involving these oscillations [1]. In general, power system oscillations are mitigated (or damped) using Power System Stabilizers (PSSs).

A PSS injects a supplementary signal to the excitation system of the synchronous generator it is connected to. This supplementary signal is generated using only local measurements, which limits its effectiveness for system-wide damping control. In [2] the authors describe the principle of operation of PSSs and provide a step-by-step methodology for designing them.

It is not clear that the conventional damping control approach using local PSSs will be effective enough to damp low-frequency interarea oscillations [3]. However, the advent of Phasor Measurement Units (PMUs) and advanced communication infrastructures has opened the door to improved damping control algorithms due to the availability of time-synchronized wide-area signals. It has been shown that controllers that make use of these signals could damp power system oscillations more effectively than conventional local controllers [3]-[4]. However, the techniques and methodologies for designing these wide-area damping controllers (WADC) are still being refined by the research community.

The work in [5] presents a decentralized/hierarchical approach for the coordinated design of PSSs that make use of wide-area signals to improve the damping of low-frequency oscillations in the Hydro-Quebec system. The approach relies on linear system identification and control design techniques, and therefore the performance of the resulting controllers is likely to degrade as the system's operating point shifts away from that used for controller design. An attempt to deal with this issue can be found in [6], where the controllers are developed using a linearized model of the power system and robust control techniques. The resulting controllers were then tuned using the full non-linear model of the system to ensure appropriate performance. A neural network based method for dealing with the non-linear and time-varying nature of power systems is presented in [7]. The adaptive nature of these controllers allows them to maintain their level of performance even as the operating conditions of the power system change. However, as the size of the system grows, the computational expenses for achieving acceptable performance from neural networks become prohibitive and make this type of controller less practical for realistically sized systems [8].

This paper exploits the tendency of groups of synchronous generators in a power system to behave coherently, and generates simplified abstract representations of portions of a power system. These new representations, termed Virtual Generators (VGs), are calculated online using wide-area measurements (WAMs). The ideas behind the development of the VG have a strong resemblance with well established methods for creating power system dynamic equivalents in large power system simulation studies. However, power system dynamic equivalents are developed offline, are fixed, and are used for replacing large portions of the system that are

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considered external to the portion of the system being analyzed. In contrast, VGs are calculated online, are not limited to representing external areas of the system being analyzed/controlled, and do not replace any portion of the power system. Instead they allow WADCs to exploit the realization that a group of several synchronous generators in a power system can be controlled as a single generating unit for achieving wide-area damping control objectives.

To the authors' knowledge, this is the first time that the use of power system equivalencing techniques has been extended to real-time WADC. Simulation studies carried out on the IEEE 68-bus New England/New York bench mark power system with 16 generators (Fig. 1) demonstrate that an intelligent controller using VGs can significantly improve the stability of a power system by injecting supplementary wide-area signals to the excitation system at a number of synchronous generators in the system to effectively damp low-frequency interarea oscillations.

The organization of the paper is a follows: Section II provides some basic concepts regarding generator coherency, coherency determination, and demonstrates those concepts via simulations of 68-bus power system. Section III introduces the VG representations, draws the parallelism between VGs and power system dynamic equivalents, and applies the VG to a portion of the 68-bus system. Section IV briefly demonstrates how VGs can be used to develop an intelligent wide-area damping controller (IWADC). Section V illustrates the effectiveness of the resulting IWADC for damping oscillations on the 68-bus system. Section VI summarizes the findings, outlines some of the current research efforts, and provides insights into some of the other potential uses of VGs for improved WADC.

II. Power System Coherency and Coherency Determination

The VG representation introduced in this paper relies on the concept of coherency. This section briefly discusses that concept, presents the method used for identifying coherent generators, and illustrates its implementation via power system simulations.

A. Generator Coherency

Coherency in power systems refers to the tendency of groups of generators to "swing together" after disturbances. Swinging together refers to generators oscillating in phase at the same angular speed and maintaining the same rotor angle deviation. This tendency has been attributed to a variety of factors such as the stiffness of the interconnection between generators and the ratio between the synchronizing torque coefficients and the inertias of the generators within a group [9].

In [10]-[11] it was demonstrated that, for certain kinds of power system studies, coherent behavior can be exploited to generate simplified dynamic equivalents of portions of power systems while maintaining acceptable simulation accuracy. These equivalents represent a number of coherent generators using a single generator model, thus greatly reducing the complexity of the simulation and speeding up simulation run-times. Typically, these equivalents are used to represent portions of the system that are outside of the area being studied, and during the studies disturbances are applied at locations electrically far away from the equivalent.

B. Coherency Identification

A variety of methods have been developed to identify groups of coherent generators. Three of these methods were evaluated in [12]: weak links (WL), two-time scale (TS), and linear time simulations (LS). The authors of that paper concluded that all three methods produced good generator grouping for creating equivalents. The LS is considered the classical method to identify coherent generators. It consists of simulating a linearized model of the power system with classical generator models and ignoring non-generator dynamics. Once the generators' swing curves (time-domain waveforms of the rotor angles) are obtained, clustering algorithms can be used to find groups of generators that exhibit strong similarity in their swing curves. The details of the LS coherency identification algorithm can be found in [10]. A more advanced technique based on modal analysis and accounting for the effect of voltage dynamics was presented in [13], but the additional clustering accuracy gains that can potentially result from that approach are considered unnecessary in the present work.

The approach in this paper is similar to the LS method; however, the full order model of the system (not a simplified and linearized version of it) is used to generate the generator swing curves. Hierarchical clustering based on these curves is then completed using tools available in MATLAB's Statistics Toolbox. This approach to generator clustering will be called *full simulation hierarchical clustering* (FSHC) in this paper.

C. The 68-Bus New England/New York Power System

Each generator in Fig. 1 is modeled by neglecting stator transients, but including a damper winding on both the d and q axes. The automatic voltage regulator (AVR)/exciter and turbine/governor models for each generator are shown in Fig. 2. The AVR has two supplementary signal input points (u_{PSS}, and u_{WADC}). When connected, these inputs correspond to the output of a local PSS and of a WADC respectively. Generators G14-G16 represent large groups of generators and have been equipped with PSSs. The power network is represented by a set of algebraic equations and the loads are represented as constant impedances. This is a reduced order model of the New England/New York interconnection of more than 30 years ago. More details on the parameters of this model can be found in [14].

The full system is simulated using DIgSILENT PowerFactory For the purposes of this paper, only the New England side of the system will be considered accessible; i.e., measurements and control inputs are only available for this portion of the system. This accounts for the fact that, in a real power system application, it is highly unlikely that a single entity would have access to the information/measurements of the entire power system.

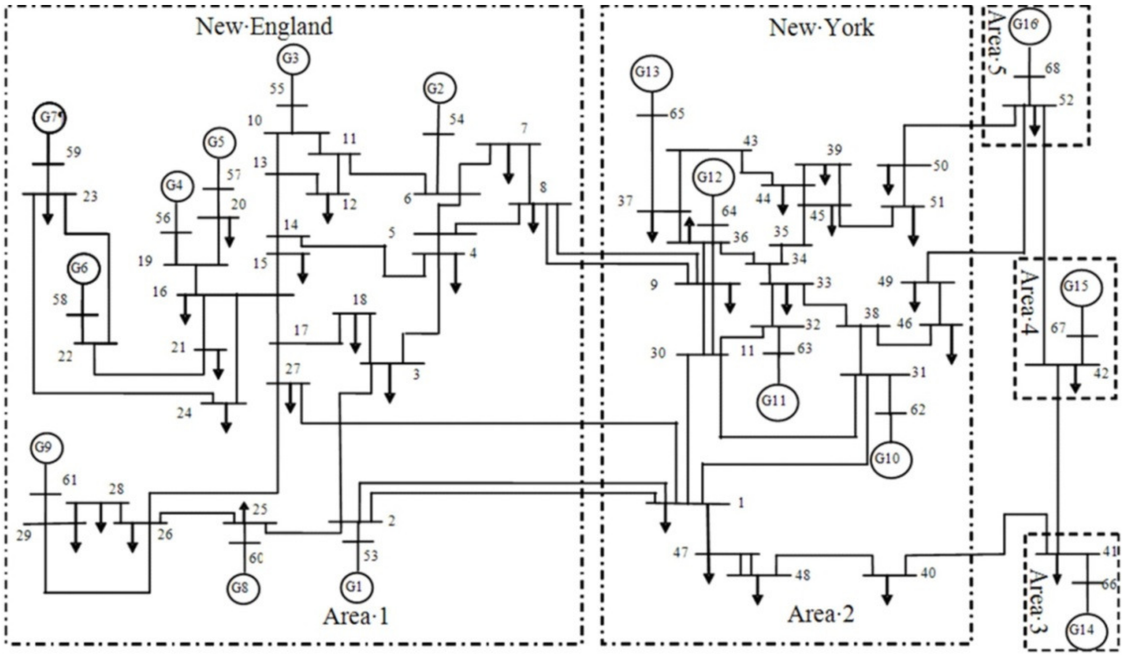

Fig. 1. Single line diagram of the 68-bus New England/New York power system

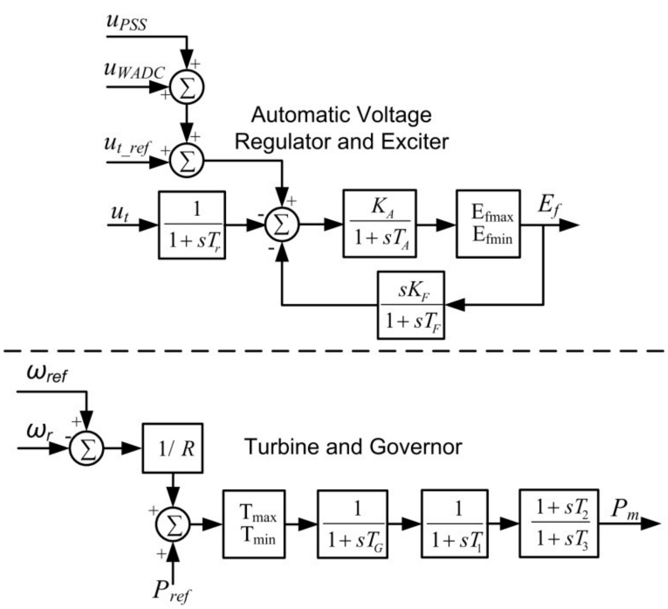

Fig. 2. Models of generator controls

D. Illustration of Coherency Determination

This section illustrates the application of coherency identification to the 68-bus system. Three-phase faults are applied at a number of locations across the system to generate the swing curves. The clustering results provided by the FSHC method are summarized in the dendrogram shown in Fig. 3. The height of the horizontal links connecting one generator to another is a measure of the dissimilarity between the swing curves. As expected, none of the generators exhibit perfect coherency. However, 4 groups of coherent generators can be formed by selecting the coherency threshold line shown in the figure: {1, 8}, {2, 3}, {4, 5, 6, 7}, and {9}.

Different groupings can be achieved simply by choosing a different threshold line, so visual inspection of the swing curves complement the dendrogram to make the final grouping selection.

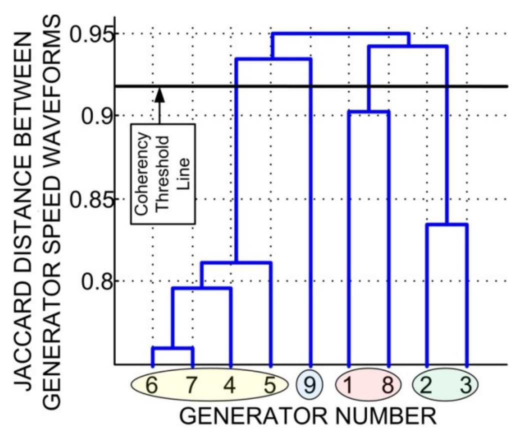

Fig. 3. Coherent generator clustering dendrogram

III. Power System Equivalents and Virtual Generators

As previously mentioned, it is possible to exploit coherency to generate simplified power system representations. One of the methods for creating such representations is called slow coherency aggregation and can be found in [15]. The idea is to define the center of angle of a group of coherent machines as a slow variable, and their inter-machine oscillations as a fast variable. The definitions of these variables for a group of say 2 machines for example, are shown in (1) and (2).

$$\delta_{slow} = \frac{H_1\delta_1 + H_2\delta_2}{H_1 + H_2} \tag{1}$$

$$\delta_{fast} = \delta_1 - \delta_2 \quad (2)$$

The constant H_i is the per unit inertia of generator i with all generators in the group referred to the same power base. Equation (1) can be differentiated to obtain:

$$\dot{\delta}_{slow} = \frac{H_1\dot{\delta}_1 + H_2\dot{\delta}_2}{H_1 + H_2} = \omega_{slow} = \frac{H_1\omega_1 + H_2\omega_2}{H_1 + H_2} \quad (3)$$

Generalizing for groups of N coherent generators results in:

$$\omega_{slow} = \frac{\sum_{i=1}^{N}(H_i\omega_i)}{\sum_{i=1}^{N}(H_i)} \quad (4)$$

The coherency assumption results in the vanishing of the fast variable in (2) to a small value that is neglected. Also, the availability of PMU data allows the real-time calculation of (4) as the system operates. As a consequence, large portions of the system containing a number of coherent generators can be represented as a single generator for wide-area damping control purposes. The resulting "equivalent" generator is called a "Virtual Generator" (VG) from now onwards. The virtual speed of the VG is defined as in (5).

$$\omega_{VG} = \omega_{slow} = \frac{\sum_{i=1}^{N}(H_i\omega_i)}{\sum_{i=1}^{N}(H_i)} \quad (5)$$

An issue with this representation is that the validity of the coherency assumption, and consequently the validity of the VG representation, varies with the system operating condition and with the type of disturbance applied as will be shown in Section III-B.

A. Simplifying the System Via Virtual Generators

Complementing the information provided by Fig. 3 with load flow studies allows the partitioning of the 68-bus network into 4 small sub-networks.

The criteria used for grouping non-generator buses are: minimize the number of sub-network interconnections, and minimize the power transfers between sub-networks. These criteria reflect the desire to have sub-networks that are as self-sufficient as possible (only import a limited amount of power). Self-sufficiency will allow for intelligent control of system islanding with minimal load shedding. This form of control is expected to improve the resiliency of the power system. WADC could potentially aid during islanded conditions and during system restoration, but this potential is not further addressed in this paper.

The resulting sub-networks are shown in Fig. 4. The New York side of the system is now shown as an external power network.

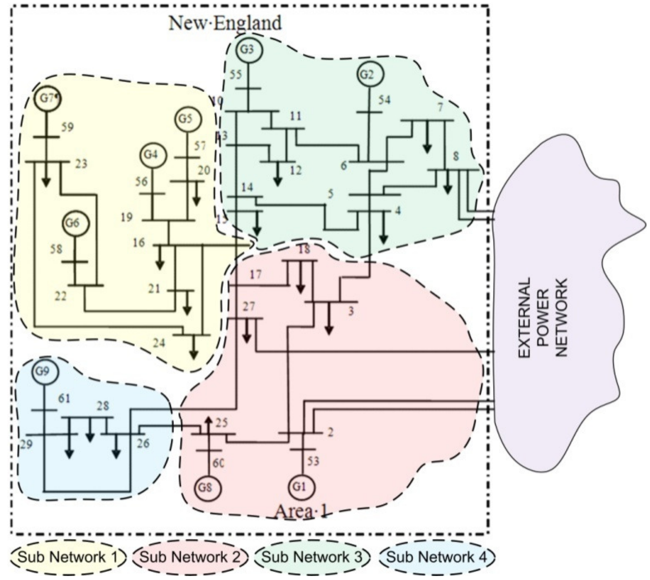

Fig. 4. Partitioning of the New England side of the 68-bus system

For wide-area damping control (WADC), the rotor speeds of the generators inside of these sub-networks can be represented using one VG per sub-network. This results in the simplified representation shown in Fig. 5.

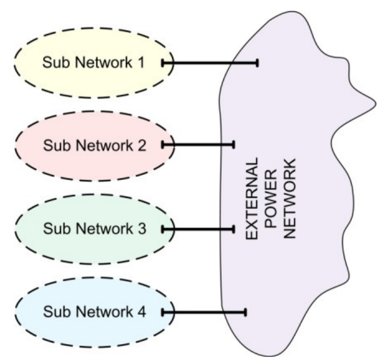

Fig. 5. Simplified representation of New England potion of the 68-bus system using VGs

Applying (5) to calculate the virtual speed for each of the 4 VGs after a disturbance in the system results in the VG speed waveforms shown in Fig. 6, and the four sub networks clearly respond in very different ways

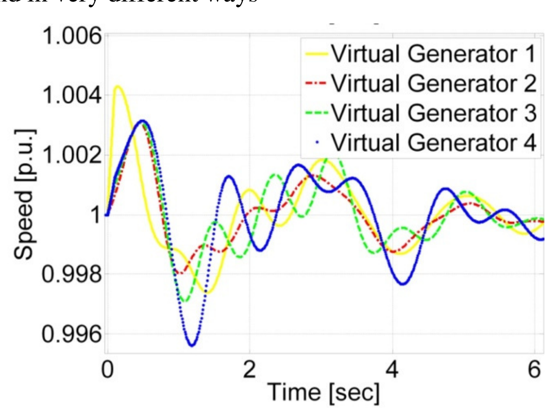

Fig. 6. VG speeds after a 3-phase short circuit disturbance

It should be emphasized that the simplifications performed so far only *resemble* power system equivalencing procedures; however, they are merely a way of *interpreting* information and measurements about the system; but the actual system has not been changed or affected in any way.

B. Grouped Generators Don't Always Behave Coherently

The VG representation is based on the assumption that all generators in a group behave coherently. However, this assumption is typically satisfied only for disturbances that occur electrically far away from the coherent group. Figure 7 shows the speed deviations of generators G4-G7 and of the VG representing these four generators in sub-network 1 (see Fig. 4) when a disturbance is applied at a remote location. The speeds of the generators are nearly identical, and the coherency assumption holds.

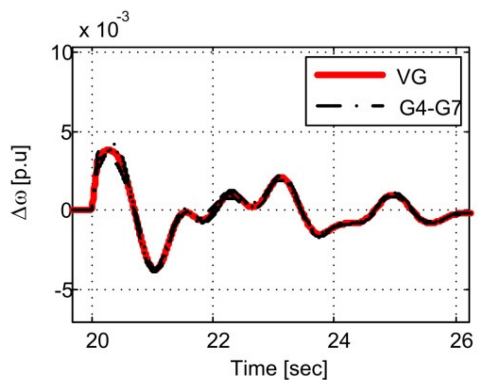

Fig. 7. Group speed deviations for disturbance applied electrically far

In contrast, when the disturbance is applied electrically close by, the coherency assumtion is violated, and the VG representation is no longer accurate as illustrated in Fig. 8 for the same sub network. Nevertheless, the results of Fig. 11 show that the good damping by the IWADC can still be achived.

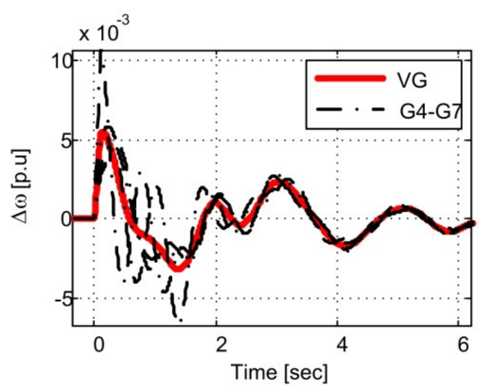

Fig. 8. Group speed deviations for disturbance applied electrically close

IV. VGs and Intelligent Wide-Area Control

So far the VG concept has been explained and its validity has been motivated by drawing the parallels between it and commonly used power system equivalencing techniques such as slow coherency aggregation. However, its usefulness is yet to be demonstrated.

This section briefly discusses how VGs can aid the development of intelligent wide-area damping controllers (IWADCs). The core idea is: *damping VG oscillations results in damping of interarea oscillations on which the coherent group participates*. Following this idea, VG based control amounts to treating the VG as a real generator in the system and designing a controller capable of damping oscillations of it. By ignoring intra-area oscillations, denoted as the fast variable and neglected due to coherency in Section III, the interactions between the WADC and local controllers at each generating unit are reduced.

When coupled with existing dynamical system identification techniques, the VG concept can potentially be used for developing many of the control algorithms currently available in the literature. However, intelligent controllers based on Approximate Dynamic Programming (ADP) in the form of Adaptive Critic Designs (ACDs) have been shown to outperform a variety of more conventional controllers for WADC [16]. Also, the ACD framework is measurement driven and avoids the need for accurate mathematical models of the system. This justifies the use of this type of controller in the current application.

Adaptive Critic Designs (ACDs) are a family of reinforcement learning mechanisms that approximate solutions of the Bellman equation of dynamic programming using differentiable structures such as (but not limited to) artificial neural networks (ANNs). ACDs based intelligent controllers have the ability to improve their performance and approach optimality over time as experience is gained through interactions with the system. The reader is pointed to [17]-[18] for an in depth treatment of ACDs. Heuristic dynamic programming (HDP), one of the simpler and less computationally expensive ACDs, is chosen for the IWADC. The integrated VG-HDP based intelligent wide-area damping controller (IWADC) is shown in Fig. 9.

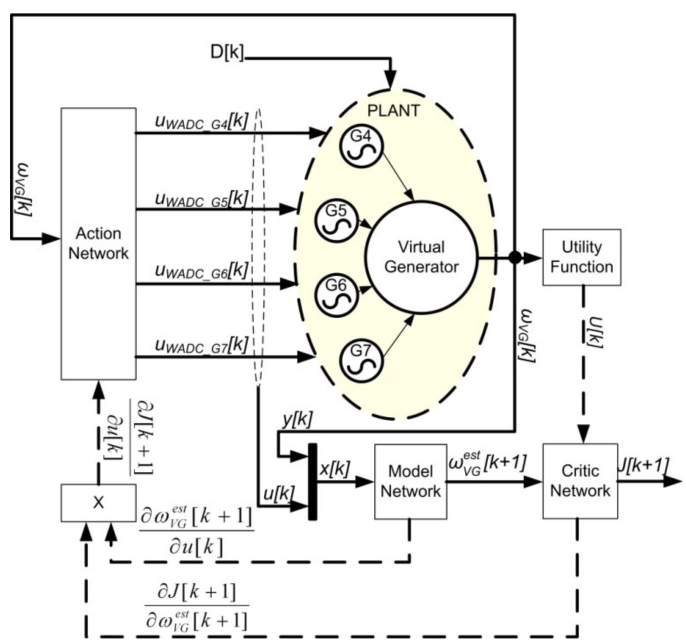

Fig. 9. HDP-based intelligent wide-area damping controller

Three ANNs are used by the IWADC in Fig. 9:

- *Model Network:* provides an input/output data driven dynamic model of the system. This ANN can be differentiated to obtain an approximation of the sensitivity of the system output (the speed of the virtual generator) to changes in the system inputs (auxiliary signals sent to the excitation system of each of the generators in the coherent group).
- *Critic Network:* provides an approximation of a discounted infinite horizon cost-to-go function that measures the performance of the system. This ANN can be differentiated to obtain an approximation of the sensitivity of the cost-to-go to changes in the system output.
- *Action Network:* implements a control policy based on measurements of the system output. The parameters of this ANN are adapted to minimize the approximated cost-to-go using the sensitivity estimates obtained from the model and critic networks.

This IWADC injects supplementary wide-area damping signals to each generator in the coherent group. These signals are received by the AVRs on each generator at the point labeled as u_{WADC} in Fig. 2. Further details about the development and implementation of the IWADC will be provided in future works.

V. Simulation Results

Three system configurations are used for evaluation purposes. The first one, the base case, is described in Section II-C. The second one consists of adding conventional linear PSSs to generators G4-G7. These PSSs use local measurements only. The third one consists of adding the IWADC as illustrated in top-left corner of Fig. 10. The IWADC receives time-synchronized wide-area measurements of the speeds of the 4 generators in the coherent group it is controlling (G4-G7) and transmits a supplementary wide-area damping control signal to the excitation system at each of those generators.

A number of intermittent as well as permanent disturbances are applied to the system in order to observe the effectiveness of the IWADC. The disturbances and their locations are listed below and shown in Fig. 10:

- 100 ms self-clearing 3-phase fault on the terminals of generator G4 at time t = 0 sec to evaluate the validity of using the VG concept, even when the fault is inside the sub network represented by the VG. The system response is shown in Fig. 11.
- Increase load L1 to 500% of the base case at time t = 20 sec
- 100 ms self-clearing 3-phase fault on the terminals of generator G4 at time t = 40 sec
- 3-phase fault at time t = 80 sec cleared after 100 ms by opening the transmission corridor connecting buses 1 and 2 (2 lines). The response is shown in Fig. 12.
- Increase load L1 to 800% of the base case at time t = 120 sec. The system response is shown in Fig. 13.

The simulation results in Figs. 11-13 demonstrate the performance of the controllers as the system gets pushed towards instability due to weakened interconnections and heavier power transfers between distant areas.

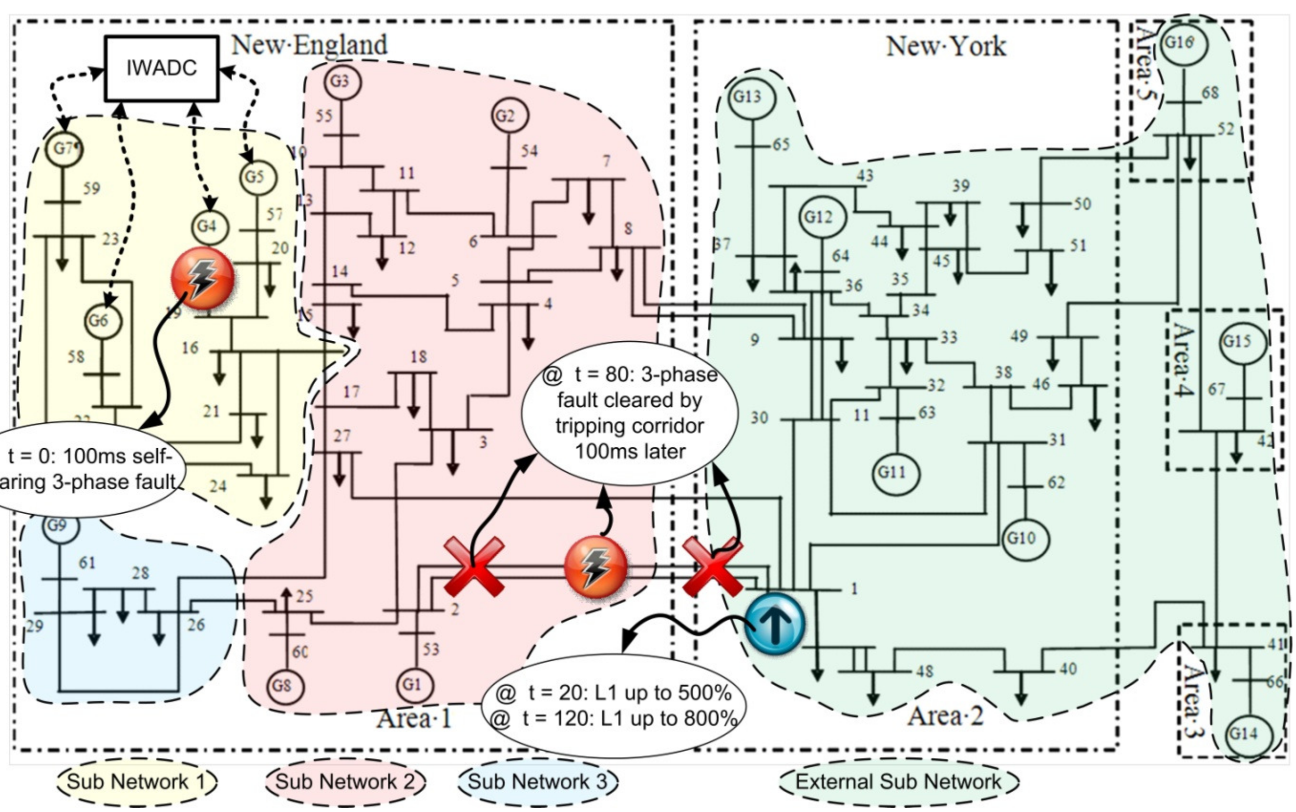

Fig. 10. 68-bus New England/New York power system with the intelligent wide-area damping controller and including simulated system events

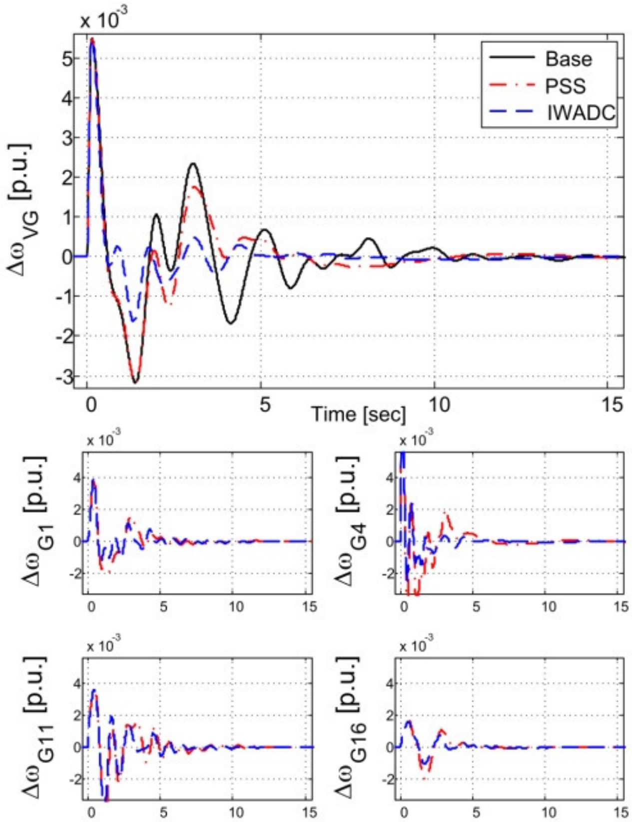

Fig. 11. VG, G1, G4, G11, and G16 speeds after a 100ms self-clearing 3-phase fault inside of sub-network 1 (terminals of G4)

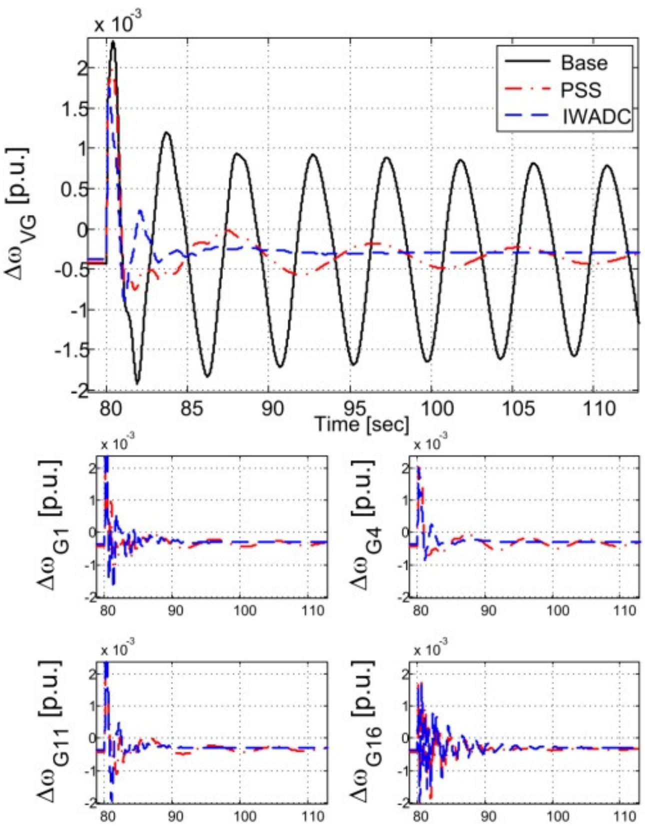

Fig. 12. VG, G1, G4, G11, and G16 speeds after a 100ms 3-phase fault cleared by opening an important transmission corridor

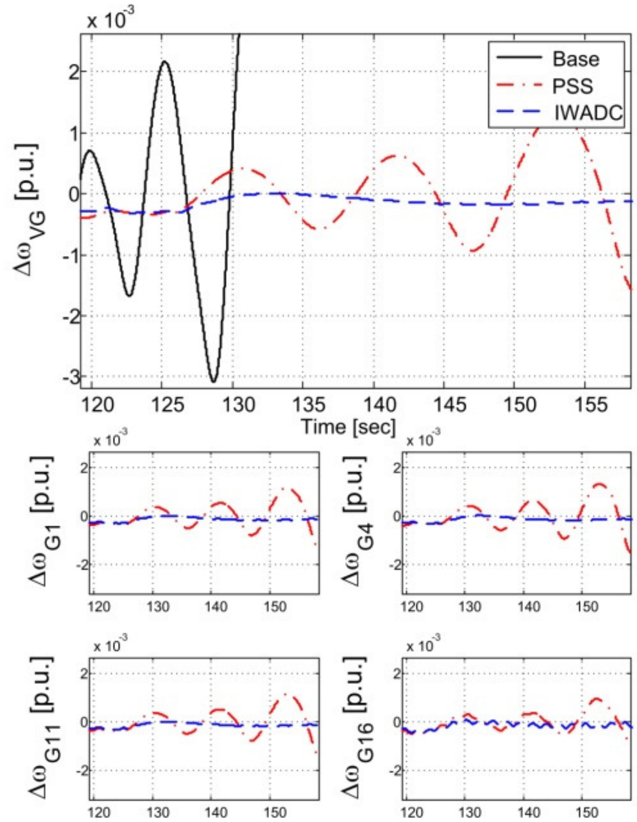

Fig. 13. VG, G1, G4, G11, and G16 speeds after a large increase in the power interchange from New England to New York

The results of Figs. 11 to 13 all show that the IWADC gives good damping. In particular Fig. 11 shows that even when the fault is located inside the sub networkon the terminals of G4, the concept of using a VG still yields better damping than the PSS, even when the coherency assumption discussed in Section III-B is not completely met.

As the system is pushed towards a heavily stressed operating condition due to the loss of an important transmission corridor interconnecting New England and New York, the inability of conventional PSSs to effectively damp interarea low-frequency oscillations becomes apparent as illustrated in Fig. 12. In contrast, the IWADC maintains appropriate damping of these oscillations.

Finally, Fig. 13 shows that utilization of IWADC can result in increased power transfers among distant areas that would result in system instability under other less sophisticated control approaches. The base case system quickly becomes unstable and the system with the 4 additional PSSs does so as well, although total system collapse occurs more slowly. However, the system with the IWADC is capable of reaching a new stable operating point quickly and with minimal oscillations.

VI. Summary and Conclusions

This paper presents a new approach for wide area control that relies on the concept of a Virtual Generator (VG). VGs are simplified abstract representations of portions of the power system that allow wide-area controllers to treat groups of several generators as if they were a single machine.

An intelligent wide-area damping controller (IWADC) is implemented in simulations to demonstrate the usefulness of the VG. It is shown that the resulting controller can in fact improve the damping of low-frequency oscillations in the system even under heavily stressed operating conditions. It is also possible to increase the power transfer capabilities among distant areas while maintaining stability even after the conventional PSSs could not. Future work will focus on the use of the VG concept for the implementation of conventional control algorithms such as linear robust PSSs. Also, the effect of transmission delays due to long distance communications must be addressed. VGs also lend themselves to multi-agent approaches, where each agent is charged with damping the oscillations of a VG representing a different sub-network.

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VII. BIOGRAPHIES

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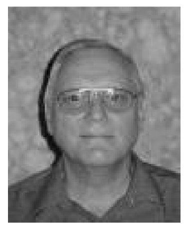

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