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# A wide-area SVC controller design for inter-area oscillation damping in WECC based on a structured dynamic equivalent model

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ABSTRACT

In our recent work [1], we constructed a reduced-order model of the Western Electricity Coordinating Council (WECC) power system using mathematically derived parameters from real Synchrophasor data. These parameters include inter and intra-area impedances, inertias, and damping factors for aggregate synchronous generators representing five geographical, and yet coherent, areas of WECC. In this paper, we use this reduced-order model as a tool to design a supplementary controller for a Static VAr Compensator (SVC), located at the terminal bus of one of the aggregate generators. Wide-area feedback consisting of phase angle and frequency measurements from Phasor Measurement Units (PMUs) in the other areas is used to design this controller. The objective is to damp the inter-machine oscillation modes of the reduced-order model, which in the full-order system corresponds to inter-area oscillations. The controller input is chosen via statistical variance analysis, and its parameters are tuned to improve the damping factors of the slow modes. The model is implemented in a real-time digital simulator, and validated using a wide range of disturbance scenarios. The closed-loop system is observed to be highly robust to all of these disturbances as well as the choice of operating points. Detailed experimental analyses of the capacity of the SVC to satisfy the damping specifications of supplementary control are also presented via multiple contingencies. The results are promising in aiding damping of inter-area modes in WECC, especially at a time of increasing penetration of wind and other renewable resources.



## 1. Introduction

The Western Electricity Coordinating Council (WECC) is responsible for coordinating and promoting bulk electric power system reliability in the western part of North America. The geographic size and diversity of the WECC leads to a special network topology with separate and well-defined generation and load centers, with long tie lines connecting these various regions. This results in *coherency* between the generators [2], and therefore, a well-defined time-scale separation of the slow and fast electro-mechanical modes of oscillation within the 500 kV network of WECC [4]. The slow oscillations, typically referred to as inter-area oscillations, are well-studied for the traditional operating conditions of the WECC. However, with gradual expansion in the transmission infrastructure as well as tremendous penetration of renewable power including wind and solar photovoltaic in the west coast over the next decade, several dynamical properties of the WECC will change significantly, and so will the characteristics of the interarea oscillations and their stability margins. Such projected changes are neither well-understood from an analytical perspective nor well-established from experiments. Our goal in this paper is to – (1) design a wide-area FACTS controller that will integrate real-time phasor measurements of voltage, phase angle and frequencies from different points in the WECC model in order to damp these inter-area oscillations over a wide range of operating conditions including unforeseen contingencies and intermittent renewable

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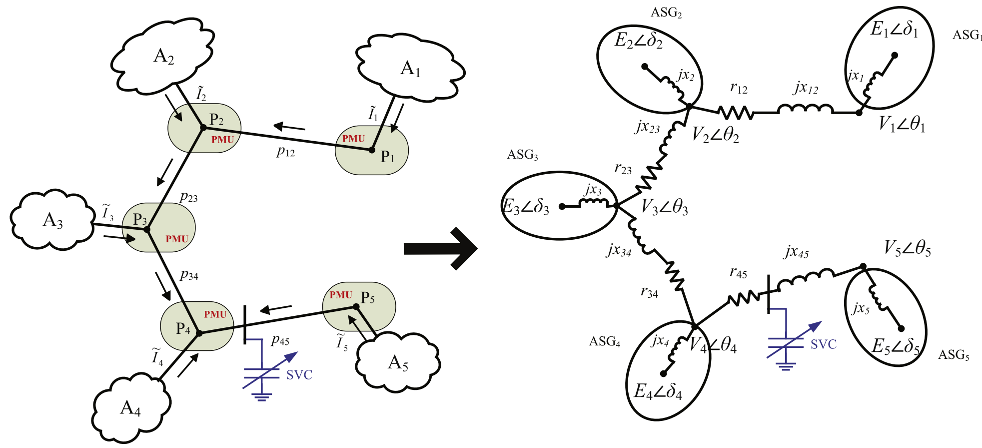


**Fig. 1.** Electrical topology of WECC's 500 kV network.

generation and (2) thereafter, validate those observations using an RTDS[2]-based emulation framework. To achieve these goals, we use a reduced-order dynamic equivalent model of the 5-area WECC system that was recently developed in our paper [1]. We start from this reduced-order swing model of the WECC, and design a wide-area supplementary controller for a Static VAr Compensator (SVC) sited between two areas. Following the Static VAr System installed in between southern California and Arizona regions of WECC [7], we choose the SVC location at an intermediate bus between areas 4 and 5, as shown in Fig. 1. The objective is to damp the oscillation modes between all the aggregate machines, which in the actual system will correspond to inter-area oscillations, i.e., oscillations between all the areas. The interesting aspect of this design is that although it is based on a reduced-order model, the designed controller can be easily implemented in the actual WECC system since the pilot buses retain their identity. Note, however, that the structure of the model mandates the controller to be in shunt configuration. For example, one will not be able to use this model to design a series controller such as a Thyristor Controlled Series Compensator (TCSC) along a transmission line connecting two areas [5,6], simply because of the fact that the tie-lines retained in the model are *equivalent* tie-lines that do not exist in the actual system. Similarly, conventional damping controllers such as Power System Stabilizers (PSS) are also not permissible for this model since all the ASG's are aggregate generators.

The basic approach for the control design presented here is twofold. First, a nominal PI controller is designed using local output feedback, and the controller gains are tuned for optimal closed-loop damping of the inter-area power flows. Thereafter, a supplementary controller is designed using remote feedback of voltages and phase angles from other pilot buses, thereby forming a wide-area control loop. Several studies have been done in recent past on FACTS/SVC design for oscillation damping [9]. Majority of these designs, however, need precise information about all the intra-area network and machine parameters surrounding the FACTS device. Our controller, in contrast, only needs aggregate model information, and PMU data feedback from the pilot buses, and therefore is much easier to design, and simpler to implement once the reduced-order model is estimated accurately.

## 2. Description of the 5-area WECC model

As mentioned in the introduction, the WECC system is divided into five non-overlapping coherent areas, connected in a linear topology through long 500 kV transmission lines following the example cited in [4]. These five areas are represented by five aggregated synchronous generators (ASG) with the interconnecting 500 kV lines between any two areas reduced to a single equivalent transmission line, as shown in Fig. 1. The lines connect five real-world sub-stations, referred to as pilot buses that are selected from each area based on two criteria – (1) the sub-station must have a PMU installed at its location and (2) all generators within that area must lie *behind* this sub-station. The voltage phasor $V_i\angle\theta_i(t)$ is known at any pilot bus $i$ owing to availability of PMU data at that bus over time $t$. Furthermore, the current $I_i\angle\alpha_i(t)$ injected at pilot bus $i$ can be calculated from the difference in line currents flowing in and out of that pilot bus, known from PMU data:

$$\tilde{I}_i(t) = \tilde{I}_{ik}(t) - \tilde{I}_{ji}(t), \quad j,\ k \in \mathcal{N}_i, \tag{1}$$

where $\mathcal{N}_i$ is the neighboring pilot bus set for $i$. The pilot bus of a particular area also acts as the terminal bus for the ASG in that area. Looking from the pilot bus into the area, this generator is modeled as a Thevenin voltage source with internal EMF $E_i\angle\delta_i$ and Thevenin reactance $jx_i$. Due to non-identifiability, it is not possible to model it as an impedance of $r_i + jx_i$ (for details please see [1]). Each ASG is modeled as a second-order damped oscillator described by the swing equations. Since these ASGs are fictitious generators, their model parameters are not known, and need to be identified using PMU measurements of voltage and phase angles measured at the corresponding pilot bus. Thus, the parameter identification for the five-area model is a three-step process: (1) identification of inter-area tie-line impedance $(r_{ij} + jx_{ij})$ connecting pilot bus $i$ to pilot bus $j$, (2) identification of Thevenin reactance $jx_i$ of ASG $i$, and (3) identification of inertia $M_i$ and damping $D_i$ of ASG $i$. Since the aggregate generators are obtained by collapsing the collections of actual coherent generators, the non-coherent modes or local modes must be removed from the PMU measurements before they can be used to identify the above three quantities for each ASG. In other words, the raw PMU data contains both fast local modes as well as slow inter-area modes, and must be passed through a band-pass filter to remove the fast modes that do not correspond to the inter-machine oscillations in the reduced-order model. However, since such filtering typically adds a phase shift to the slow modes, distorting the data, an alternative approach is to use time-domain decomposition methods, also typically referred to as subspace identification or modal decomposition. Commonly used modal decomposition methods include Prony and Eigensystem Realization Algorithm (ERA) [8], which are time-domain based curve-fitting techniques that can be used to determine frequency, amplitude, phase and damping components of the 'equivalent' PMU measurements from the pilot buses.

[2] Real-Time Digital Simulator.