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# Intelligent Integration of a Wind Farm to an Utility Power Network with Improved Voltage Stability

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**Abstract**— The increasing effect of wind energy generation will influence the dynamic behavior of power systems by interacting with conventional generation and loads. Due to the inherent characteristics of wind turbines, non-uniform power production causes variations in system voltage and frequency. Therefore, a wind farm requires high reactive power compensation. Flexible AC Transmission Systems (FACTS) devices such as SVCs inject reactive power into the system which helps in maintaining a better voltage profile. This paper presents the design of a linear and a nonlinear coordinating controller between a SVC and the wind farm inverter at the point of interconnection. The performances of the coordinating controllers are evaluated on the IEEE 12 bus FACTS benchmark power system where one of the generators is replaced by a wind farm supplying 300 MW. Results are presented to show that the voltage stability of the entire power system during small and large disturbances is improved.

**Keywords** –*adaptive control, coordinating control, direct drive synchronous generator, FACTS devices, neural networks, power system, SVC, voltage stability, wind farm.*

## I. INTRODUCTION

In the past, wind energy used to contribute a very small fraction of the electrical power system network. Today, this has changed dramatically with more wind energy penetrating the conventional power network. The amount of electricity being generated by wind turbines is increasing continuously. In next 10 years, the wind energy is expected to be in a proportion comparable to energy produced from the conventional steam, hydro and nuclear systems so that any adverse effect of wind generation integration would jeopardize the stability of the system. With the current integration and control schemes, the impact of wind energy integration has adverse effects on the dynamics of the already stressed power system in USA [1].

The earlier fixed speed generators with variable gear mechanical couplings used to generate electricity with a low efficiency. In the recent years, variable speed wind generators have been incorporated using power electronic converters to decouple mechanical frequency and electric grid frequency. The power electronic components are very sensitive to over currents because of their very short thermal time constants [2]. They sense a small voltage drop in the terminal voltage instantly and the wind turbine is quickly disconnected from the grid to protect the converter. This can lead to instability even a

wide-spread blackout when a power system with high wind penetration is disconnected as a result of a small drop in the voltage. For the integration of wind generation to the utility grid, the voltage profile of the bus at the point of common coupling (PCC) is critical. Thus, it is necessary to maintain and control the bus voltage at the PCC under different operating conditions. Flexible AC Transmission System (FACTS) devices such as Static Var Compensators (SVCs) and Static Compensators (STATCOMS) are power electronic switches used to control the reactive power injection at the PCC, thereby regulating the bus voltages.

Various papers have suggested methods to control the bus voltage with SVCs on the system. It has been shown in [3], [4] and [5] that the voltage profile of the power system can be improved with SVCs and STATCOMs. Coordination among the voltage compensating devices leads to better performance and improves stability in the system. Linear control techniques use PI controllers which are tuned for nominal operating condition to achieve acceptable performances. The drawback of such PI controllers is that their performance degrades as the system operating conditions change. Thus, nonlinear controllers can provide good control capability over a wide range of operating conditions [6]. They can compensate for the dynamics of wind farms through adaptation of the controller parameters.

This paper presents the design of a linear and a nonlinear coordinating controller between a SVC and the wind farm inverter at the point of interconnection. The nonlinear coordinating controller is designed using a neural network to provide auxiliary wide area stabilizing signals to the references of the individual PI controller on the SVC and the wind farm inverter. A linear controller provides control signals around the nominal operating point whereas a nonlinear neural network based controller provides appropriate control signals for a wide range of operating region. The proposed design is implemented on the IEEE 12 bus benchmark power system replacing one of the generators with a wind farm.

The paper is organized as follows. Section II describes the IEEE 12 bus FACTS benchmark power system and the wind farm used in this study. Section III describes the design of linear and nonlinear coordinating controllers. Section IV describes simulation results. Finally, the conclusions are given in Section V.

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## II. IEEE 12 BUS FACTS BENCHMARK POWER SYSTEM

The IEEE 12 bus FACTS benchmark system shown in Fig. 1 consists of six 230 kV buses, two 345 kV buses and four 22 kV buses [7]. There are three areas in this system consisting of a hydrogenerators (G2) and G4, in Areas 1 and 3 respectively, and a thermal generator (G3) in Area 2 as shown in Fig.1. This power system is specifically designed to study the applications of FACTS technology. A fixed capacitor and a SVC are placed at bus 4 to improve its voltage profile during steady and transient conditions. Parameters of governors and turbines are given in [8]. For this study, the hydrogenerator in Area 3 is replaced by wind farm supplying 300 MW.

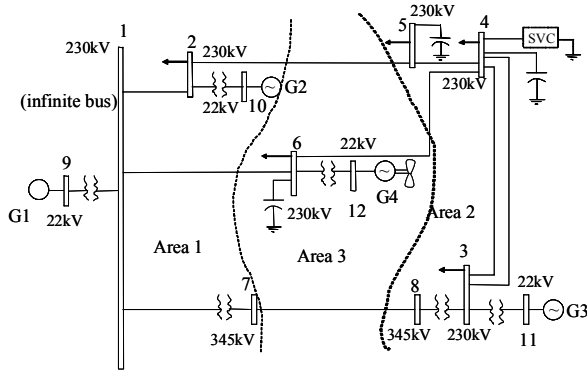


Figure 1. IEEE 12 Bus FACTS benchmark power system with a wind farm at bus 12 and a SVC at bus 4.

The wind farm is connected to the power system at bus 12 in Fig. 1. The wind farm is represented by the aggregated model of variable speed wind turbines and synchronous generators with a full scale frequency converter. The wind farm consists of 170 synchronous generators each generating a power of approximately 1.8 MW. Fig 2 shows the connection of the wind farm to the grid through a full scale frequency converter.

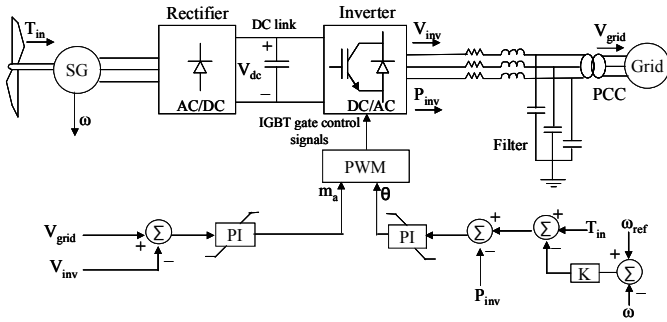


Figure 2. Block diagram of the direct drive synchronous generator based wind farm.

The wind farm is decoupled from the system with a D.C link. The disturbances and behavior of the wind farm on the generator side do not affect the grid side. The wind farm power output is first rectified by a three phase diode bridge rectifier. The dc link consists of a fixed capacitance used for voltage

compensation. The switching at the grid side inverter maintains a constant voltage at the link and allows power to flow from the rectifier to the grid.

The voltage and the power delivered by the wind farm are controlled by inverter. The PWM module has two control inputs, the modulation index ( $m_a$ ) and the phase angle ( $\theta$ ). The voltage at the PCC is controlled by the modulation index of the inverter. The phase angle controls the amount of active power delivered by the wind farm. Two PI controllers are used whose output gives the PWM control signals -  $m_a$  and  $\theta$  which generates the switching pulses to the inverter. The difference between the reference voltage at the grid ( $V_{grid}$ ) and the inverter voltage ( $V_{inv}$ ) is given as input to one of the PI controllers to generate  $m_a$ . The difference between the torque input ( $T_{in}$ ) and deviation in generator speed produce variable power reference signal ( $P_{ref}$ ). The difference between the  $P_{ref}$  and the actual power output of the inverter, ( $P_{inv}$ ) is given as input to the second PI controller whose output  $\theta$  controls the power flow into the PCC. Parameters of the PI controllers are tuned such that the controller provides satisfactory and stable performance when the system is subjected to small changes in reference values as well as large disturbances such as three phase short circuits on the power network. In this study, a constant wind speed of magnitude 15 m/sec is assumed.

The power transfer from the wind farm to the network is dependant on the voltage at the PCC. The inverter operates as local reactive compensation source and maintains constant voltage at the PCC. The active power flow ( $P_{inv}$ ) from the wind farm to the network is given by (1).

$$P_{inv} = V_{inv}V_{grid}\sin(\theta_{inv}-\theta_{grid})/X \quad (1)$$

Where  $(\theta_{inv}-\theta_{grid})$  is the phase difference between  $V_{inv}$  and  $V_{grid}$  voltages and  $X$  is the net reactance between the inverter and the PCC.

## III. COORDINATING CONTROLLER

This section describes the design of the coordinating controllers. Individually, the SVC and wind farm inverter can improve the voltage profile of the power system. Through proper coordination, better performance can be achieved avoiding any adverse affects [9]. Fig. 3 shows the schematic diagram of the coordinating controller.

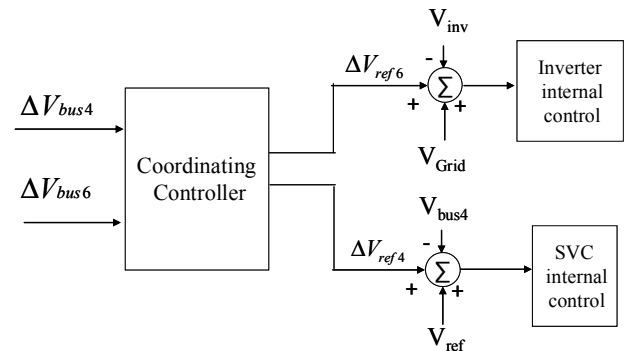


Figure 3. Block diagram of the coordinating controller.

The inputs to the coordinating controller are the deviations of voltages at bus 4 and bus 6 in Fig. 1. The outputs of the controller are added to the reference values of the respective PI controllers of the SVC and the wind farm inverter. The design of the linear and nonlinear coordinating controllers are described below.

### A. Linear External Coordinated Controller

Fig. 4 shows the schematic diagram of the linear coordinating controller. The inputs to the controller are deviations in voltage at PCC of SVC and wind farm inverter. The outputs  $\Delta V_{ref4}$  and  $\Delta V_{ref6}$  are added to internal controller references of the SVC and the inverter respectively. Two lead-lag compensators have been used in the control design. The SVC internal controller in this case is a Proportional-Integral (PI) control. The parameters of these lead-lag compensators are determined to provide best performance around a nominal operating region. Hence, a nonlinear controller may yield an optimal performance at various operating regions.

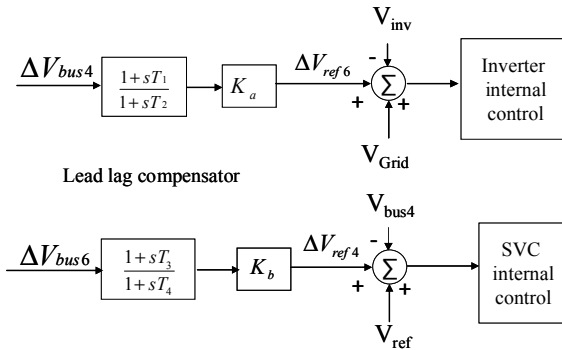


Figure 4. Linear coordinating controller.

### B. Nonlinear Coordinating Controller

Nonlinear controllers based on neural networks can provide good control capability over a wide range of operating conditions. The design of the nonlinear controller is based on an adaptive inverse model given in Fig 5. The inputs to the nonlinear controller are voltage deviations at buses 4 ( $\Delta V_{bus4}$ ) and 6 ( $\Delta V_{bus6}$ ), deviation in susceptance at the output of the PI controller of the SVC ( $\Delta B$ ) and deviation in the modulation index of the wind farm inverter controller ( $\Delta m_a$ ).

The neural network first identifies the dynamics of the system. The neural network outputs are  $\Delta V_{bus4}$  and  $\Delta V_{bus6}$ . In order to generate coordinating control signals, the neural network model is used to predict the voltage deviations at the next time step. The difference between the predicted outputs and a Desired Response Predictor (DRP) is backpropagated through the network to obtain the control signals  $\Delta V_{ref4}$  and  $\Delta V_{ref6}$ . The DRP is an optimal predictor designed on the basis of guiding the disturbed output variables to a desired steady operating point or set [10]. To derive a maximum benefit of the control signal, the DRP in this case is considered to be zero. The control signals obtained are accurate under all operating conditions since the neural network tracks the changes in the system dynamics at all times.

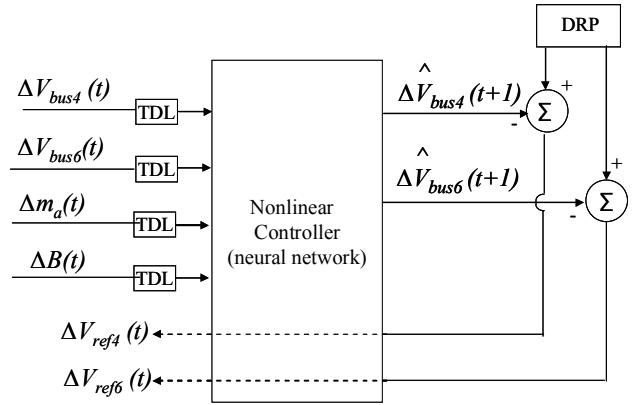


Figure 5. Nonlinear coordinating controller.

The neural network structure for the controller as shown in Fig. 6 is a three layer feedforward structure with twelve inputs, a single hidden layer with twenty neurons and two outputs. The inputs are time delayed by 10 ms and, together with eight previously delayed values, form the twelve inputs. A bias of 1 is used. A constant excitation voltage reference is applied to the generators G3 at a particular steady state operating point. Then the controller is trained by adding pseudo-random binary signals (PRBS) for system identification. PRBS signals are applied to the  $m_a$  of the inverter internal control, and susceptance  $B$  of SVC internal control. These PRBS signals excite the full range of the dynamic response of the power system [10]. The PRBS signals provide  $\pm 10\%$  deviations in the steady state values of  $m_a$ ,  $B$ . PRBS applied to generator excitations are of frequencies 5 Hz, 3 Hz and 2 Hz, that added to  $B$  are of frequencies 1 Hz, 3 Hz and 4 Hz, and that added to  $m_a$  are of frequencies 2 Hz, 3 Hz and 4 Hz.

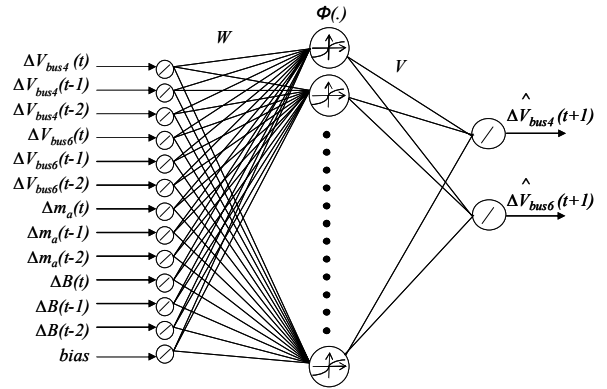


Figure 6. Neural network architecture of the controller.

Once the neural network is online trained with PRBS signals, it is then trained with natural disturbances like three phase short circuits and transmission line outages. The backpropagation algorithm is used to train the neural network.

## IV. RESULTS

This section presents simulation results obtained with linear and nonlinear coordinated controllers. The nonlinear controller

based on the adaptive inverse model is first trained to identify the dynamics of the system subject to small disturbance like PRBS. Fig. 7 shows a typical PRBS signal applied to the modulation index of the inverter in the wind farm and Fig. 8 shows corresponding voltage deviation of bus 4,  $\Delta V_4$ . It can be seen the nonlinear controller is able to predict the voltage deviations accurately.

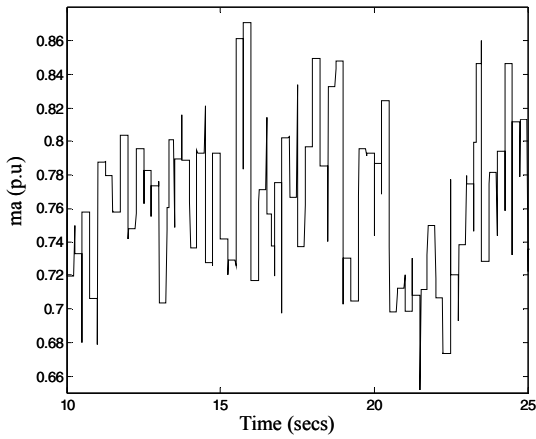


Figure 7. PRBS signal applied to the control signal of inverter, modulation index.

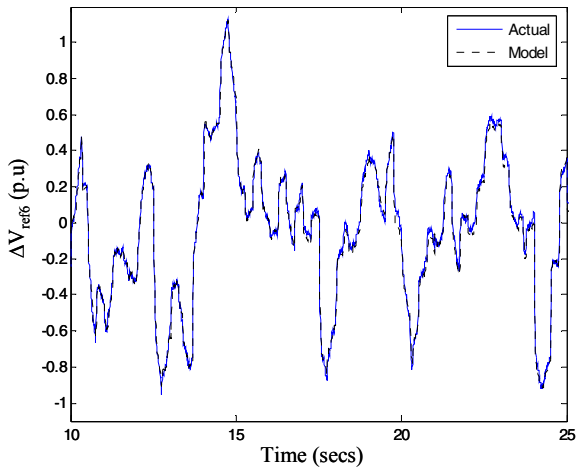


Figure 8. Actual and model predictions of voltage deviation of bus 6 for PRBS signals applied.

Several tests are carried out to evaluate the impact of the linear and the nonlinear coordinating controllers on the voltage profile of the power system. The outputs of the coordinated controllers are limited to  $\pm 0.075$  pu. Figs. 9 and 10 show voltage deviation of bus 4 and 6 respectively for a transmission line outage between buses 1 and 2 of 200 ms duration and then a three phase short circuit fault of 200 ms duration at bus 7. It can be seen that the linear and nonlinear coordinating controllers restore the voltages at the respective buses to their setpoints quickly. Figs. 11 and 12 show the corresponding control signals added to the SVC and wind farm inverter by the coordinating controllers respectively. The

control effort by the nonlinear controller is less intense compared to the linear controller as seen in Fig. 12.

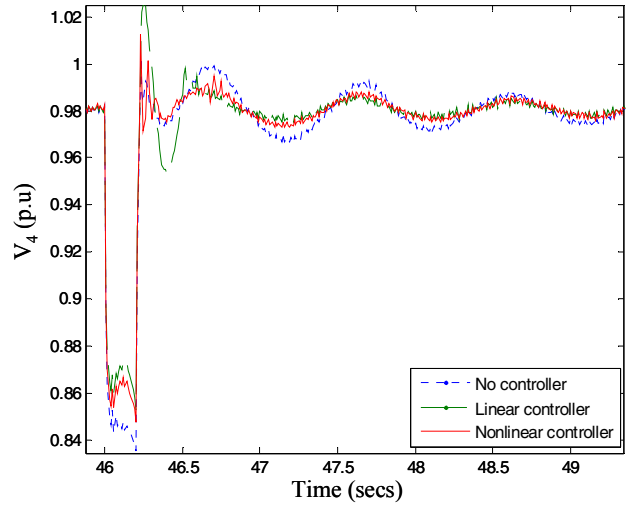


Figure 9. Voltage at bus 4 for a transmission line outage between buses 1 and 2 of 200 ms duration and then a three phase short circuit fault of 200 ms duration at bus 7.

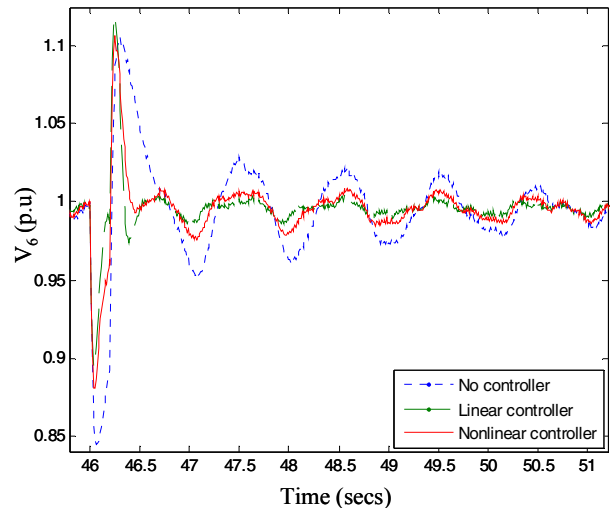


Figure 10. Voltage at bus 6 for a transmission line outage between buses 1 and 2 of 200 ms duration and then a three phase short circuit fault of 200 ms duration at bus 7.

Fig. 13 shows voltage deviations of bus 6 for two transmission lines outage of 200 ms duration between buses 3 and 4 in Fig. 1. Fig. 14 shows the corresponding control signals added to the wind farm inverter.

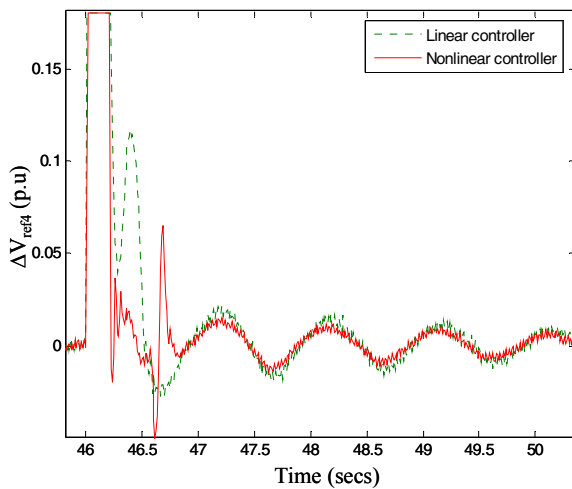


Figure 11. Corresponding control signal for Fig. 8, added to the SVC internal control reference.

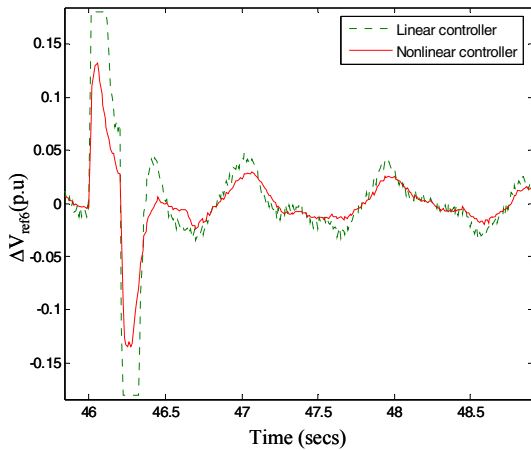


Figure 12. Corresponding control signal for Fig. 9, added to the wind farm inverter internal control reference.

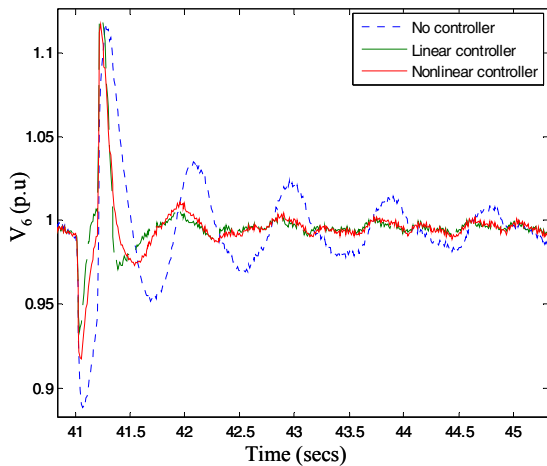


Figure 13. Voltage at bus 6 for two transmission lines outage of 200 ms duration between buses 3 and 4.

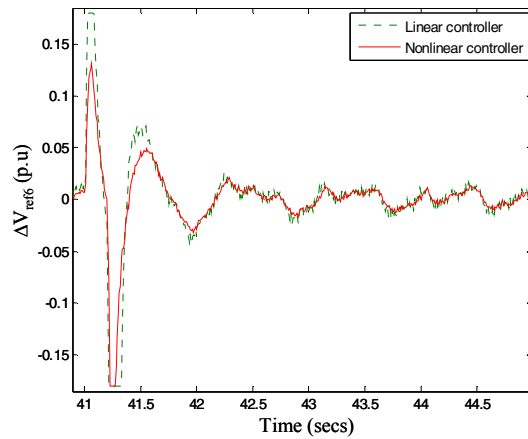


Figure 14. Corresponding control signal for Fig. 12, added to the wind farm inverter internal control reference.

## V. CONCLUSIONS

The paper has presented the successful integration of a direct driven synchronous generator based wind farm to the IEEE 12 bus FACTS benchmark system. The power system is equipped with a SVC to improve the voltage profile. The reactive power compensation provided by the wind farm inverter and the SVC are coordinated to achieve better voltage profile for the entire power system. This paper has presented two different coordination methodologies based on conventional linear control and adaptive neural network control. The coordinating controllers restore the bus voltages to their setpoints quickly after system disturbances. The nonlinear coordinating controller requires less control effort to achieve similar performance of the linear controller.

Future work involves validation of these coordinating controllers on a real-time platform. In addition, the use of STATCOMs and their coordination with the wind farms using intelligent optimal control methodologies such as adaptive critic designs can be investigated.

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