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A Neural Network based Optimal Wide Area Control Scheme for a Power System

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Abstract— **With deregulation of the power industry, many tie lines between control areas are driven to operate near their maximum capacity, especially those serving heavy load centers. Wide area control systems (WACSs) using wide-area or global signals can provide remote auxiliary control signals to local controllers such as automatic voltage regulators, power system stabilizers, etc to damp out inter-area oscillations. This paper presents the design and the DSP implementation of a nonlinear optimal wide area controller based on adaptive critic designs and neural networks for a power system on the Real-Time Digital Simulator (RTDS®). The performance of the WACS as a power system stability agent is studied using the Kundur's two area power system example. The WACS provides better damping of power system oscillations under small and large disturbances even with the inclusion of local power system stabilizers.**

Keywords-wide area control; neural networks; heuristic dynamic programming; real-time digital simulator (RTDS®); DSP implementation; power system stability; optimal control

I. INTRODUCTION

The general configuration of a modern power system is that power sources and loads are widely dispersed. Generators and loads may be hundreds of miles away. The number of bulk power exchanges over long distances has increased as a consequence of deregulation of the electric power industry. Usually, distributed control agents are employed to provide reactive control at several places on the power network through power system stabilizers (PSSs), automatic voltage regulators (AVRs), FACTS devices, etc. The PSSs are designed to have fixed parameters derived from a linearized model around a certain operating point. Final settings are made using field tests at a couple of operating points. The inherent nonlinearity in the system becomes a major source of model uncertainty. The model uncertainty includes the inaccuracies in modeling the transformers, the transmission lines and the loads.

Although local optimization is realized by these agents (PSSs, AVRs), the lack of coordination among the local agents may cause serious problems, such as inter-area oscillations. In order to minimize the problems encountered in a distributed power network control, a centralized wide area control system (WACS) is proposed [1, 2]. The WACS coordinates the actions of the distributed agents by for example using SCADA (Supervisory Control And Data Acquisition), PMU (Phasor Measurement Unit) or other wide-area dynamic information [2, 3]. The WACS receives information/data of different areas in the power system and based on some predefined objective functions, sends appropriate control/feedback signals to the distributed agents in the power network to enhance the system dynamic performance [2, 4].

The major motivation to have a wide area monitoring and control scheme is for the following benefits: 1). Transmission capacity enhancement can be achieved by on-line monitoring of the system stability limits and capabilities; 2). Power system reinforcement based on feedback obtained during analysis of system dynamics; 3). Introduction of a coordinated approach for the execution of stabilizing actions in case of severe network disturbances; 4). Triggering of additional functions by a WACS; 5). Better understanding of the dynamic behavior of the system.

Neural networks are able to identify and control multiple-input-multiple-output time varying systems as turbogenerators [5, 6] and, with continually online training these models can track the dynamics of these systems thus yielding adaptive identification for changes in operating points and conditions. Adaptive critic designs have been reported in literature to provide nonlinear optimal control for complex processes and systems [7-10].

This paper presents the design of an optimal wide area control system based on adaptive critics and neural networks for a power system. In addition, this WACS is implemented on the M67 DSP which is interfaced to the Real-Time Digital Simulator (RTDS) that runs the power system. The rest of the paper is organized as follows. Section II describes the multimachine power system studied. Section III describes the wide area control system proposed in this work. Section IV explains the implementation platform for the WACS – the RTDS® and the M67 DSP. Section V presents the implementation results. Finally, the conclusion is given in Section VI.

The support from the National Science Foundation under the CAREER Grant: ECS # 0348221 and ECS # 0400657 is gratefully acknowledged for this work.

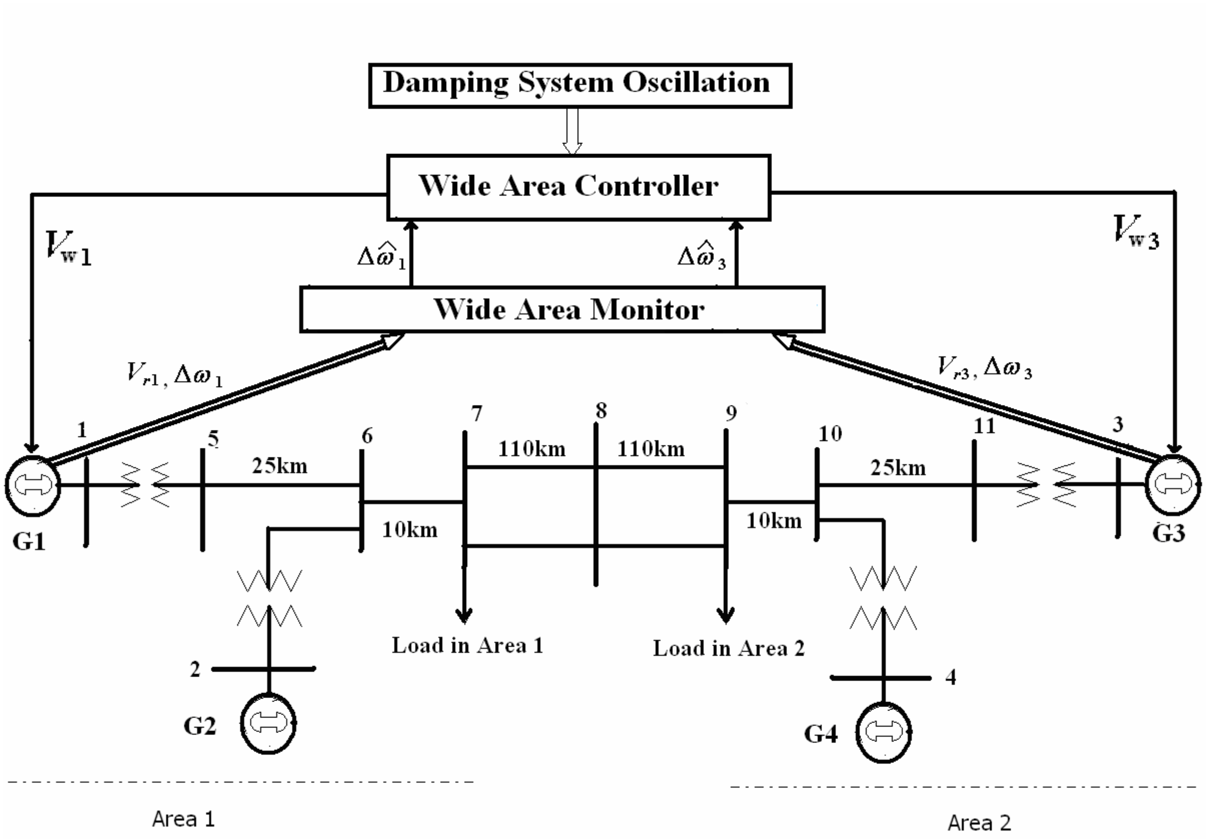

Figure 1. Two-area power system with WACS consiting of a WAC and a WAM

II. MULTIMACHINE POWER SYSTEM

In spite of being a small test system, the two-area power system of Fig. 1 mimics very closely the behavior of typical systems in actual operation and is a useful system in the study of interarea oscillations like those seen in large interconnected power systems [11, 12]. The two-area system shown in Fig. 1 consists of two fully symmetrical areas linked together by two transmission lines. Each area is equipped with two identical synchronous generators rated 20 kV/900 MVA. All the generators are equipped with identical speed governors and turbines, and exciters and AVRs. Generators G1 and G3 are equipped with PSSs (Fig. 2). Load is represented as constant impedances and split between the areas in such a way that area 1 is transferring about 413MW to area 2. Three electro-mechanical modes of oscillation are present in this system; two inter-plant modes, one in each area, and one inter-area low frequency mode, in which the generating units in one area oscillate against those in the other area. The parameters of the system are given in the appendix. The two-area power system is simulated on the real-time digital power system [13]. The simulator platform is explained in Section IV.

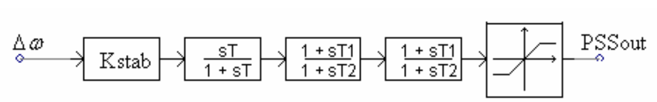

Figure 2. PSS on generator G1 and G3

III. WIDE AREA CONTROL SYSTEM

The wide area control system is based on Adaptive Critic Designs (ACDs). ACDs are neural network based designs capable of optimization over time under conditions of noise and uncertainty. Families of ACD were proposed as new optimization techniques, combining concepts of reinforcement learning and approximate dynamic programming [8]. There are many types of ACDs. The adaptive critic method determines optimal control laws for a system by successively adapting two neural networks, namely, an action neural network (which dispenses the control signals) and a critic network (which learns the desired performance index for some function associated with the performance index). These two neural networks approximate the Hamilton-Jacobi-Bellman equation associated with optimal control theory. The adaptation process starts with a non-optimal, arbitrarily chosen control by the action network; the critic network then guides the action network toward the optimal solution at each successive adaptation. During the adaptations, neither of the networks needs any "information" of an optimal trajectory, only the desired cost needs to be known. Furthermore, this method determines optimal control policy for the entire range of initial conditions and needs no external training, unlike other neuro-controllers [7].

In this work, the Heuristic Dynamic Programming (HDP) ACD design is adopted for the wide area control system and is illustrated in Fig. 3 [7]. The WACS is designed to provide

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auxiliary damping to generators G1 in area 1 and G3 in area 2 as illustrated in Fig. 1. The WACS consists of three neural networks; the critic neural network, the action network (WAC) and the model neural network (WAM), as explained below.

The critic network in the HDP approximates the cost-to-go function *J*, of Bellman's equation of dynamic programming, shown in (1). The objective of the critic and action network is to minimize (2) and (3) respectively. The action network is referred to as the Wide Area Controller (WAC). The critic network is a three layer feedforward neural network with six inputs, a single hidden layer with ten neurons and two outputs. The two outputs of the critic network represent the cost-to-go functions for generators G1 in area 1 and G3 in area 2. Each area is given a separate cost-to-go function. The critic network training procedure is as explained in [7, 9].

$$J_k^c = \sum_{k=0}^{\infty} \gamma^k u(t+k) \tag{1}$$

where $u(t)$ is the utility function and γ is the discount factor (between 0 and 1).

$$e_c(k) = \gamma J_{k+1}^c(\hat{Y}_M(k+1)) + U_k(Y(k)) - J_k^c(\hat{Y}_M(k)) \tag{2}$$

$$e_A(k) = \frac{\partial J^c(k)}{\partial A(k)} = [\frac{\partial J^c(k)}{\partial V_{w1}}, \frac{\partial J^c(k)}{\partial V_{w3}}] \tag{3}$$

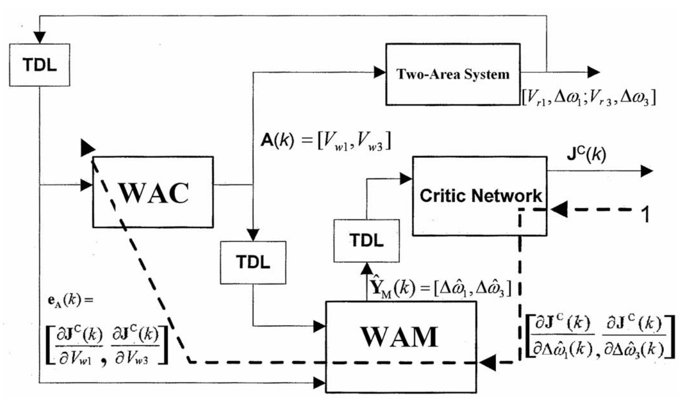

Figure 3. Heuristic dynamic programming based WACS design

The HDP design is a model dependent ACD and requires the model of the two-area power system. This dynamic model is referred to as the Wide Area Monitor (WAM) in this paper. The WAM is a three layer feedforward neural network with twelve inputs, a single hidden layer with fifteen neurons and two outputs. The WAM estimates the speed deviations of G1 and G3 (Fig. 4) based on the past speed deviations and inputs to the respective excitation systems. The training of the WAM neural network is carried out using the backpropagation algorithm [14].

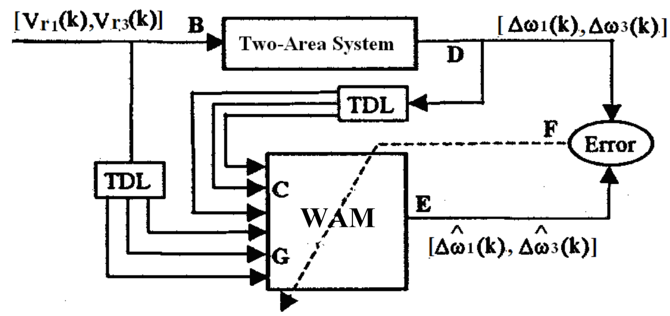

Figure 4. Wide area monitor (WAM) network training

The WAC is a three layer feedforward neural network with six inputs, a single hidden layer with ten neurons and two outputs. The inputs to the action network are the actual speed deviations of G1 and G3, and each of these inputs is together with two previously delayed values, form the six model network inputs. The two outputs of the WAC, V_{w1} *and* V_{w3}, are voltage additions to G1 and G3's AVR inputs respectively. The training procedure of the WAC is similar to those in [7, 9].

IV. Real Time Implementation Platform For The Wide Area Control System

Due to the complexity and expensive nature of the power system, it is very difficult to test new control schemes on the practical power system. The proposed WACS is implemented on a digital signal processor and its performance is tested on the two-area power system which is simulated on a real-time power system simulation platform, the RTDS®.

The RTDS is a fully digital power system simulator capable of continuous real time operation. It performs electromagnetic transient power system simulations with a typical time step of 50 microseconds utilizing a combination of custom software and hardware. The proprietary operating system used by the RTDS guarantees "hard real time" during all simulations [13]. It is an ideal tool for the design, development and testing of power system protection and control schemes. With a large capacity for both digital and analogue signal exchange (through numerous dedicated, high speed I/O ports) physical protection and control devices are connected to the simulator to interact with the simulated power system.

The real time simulator software is divided into two main categories, namely the graphical user interface and the underlying solution algorithms for network equations and component models. All aspects of simulator operation, from constructing simulation circuits through to recording simulation results, are controlled through the user friendly graphical interface RSCAD. RSCAD was developed to address practical issues encountered when performing real time simulation studies. There are two main RSCAD modules, the Draft and the RunTime. The Draft software module is used for circuit assembly and parameter entry. The window is divided into two, with the circuit assembly area on the left, and the library window on the right. The RunTime software module is used to control the operation of the RTDS simulator. Through the RunTime, the user performs actions such as the starting and stopping of simulation cases, initiating system disturbances, changing system set points, on-line monitoring of system

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quantities, triggering data acquisition and transient fault recordings as well as many other operator/control functions. Report ready plots can also be printed directly from RunTime.

The WACS consisting of the WAM and WAC is implemented on the Innovative Integration M67 DSP card (based on the TMS3206701 processor), operating at 160 MHz, hosted on a Pentium III 433 MHz personal computer. The M67 DSP card is equipped with two A4D4 modules [15]. Each A4D4 module is equipped with four analog-to-digital (A/D) converters and four digital-to-analog (D/A) converters. The DSP (WACS) and RTDS® (power system) interface and laboratory is shown in Figs. 5 and 6 respectively. For the WACS development, a sampling frequency of 40 Hz (period of 25 ms) is used.

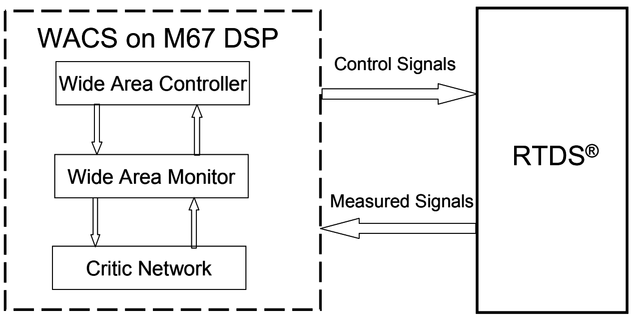

Figure 5. Block diagram of the M67 DSP (WACS) and the RTDS® interface

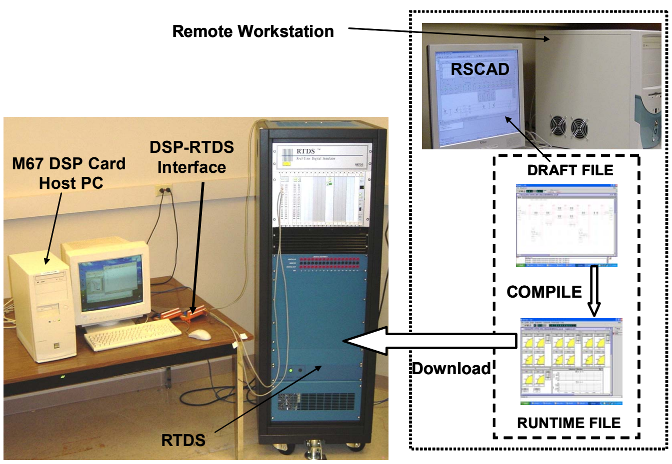

Figure 6. Laboratory hardware setup with the RTDS®

V. Implementation Results

The implementation results of WACS consisting of the wide area monitor (WAM) and the wide area controller (WAC) are given below.

A. Wide Area Monitor (WAM)

The training of the WAM consists of two phases of training namely: the *forced training* and *natural training* [6, 7, 9]. Forced training refers to training of the WAM with pseudorandom binary signals (PRBS) applied to the excitation systems of the generators. Natural training refers to training of the WAM under natural disturbances such as transmission line outage, load changes and faults. Typical forced and natural testing results of the WAM are shown in Figs. 7, 8 and 9. The estimated speed deviation by the WAM (shown by the red line) is compared with the actual generator speed deviations (blue line). Figs. 7 and 8 show the results when PRBS signals are added to the excitation systems of G1 and G3. Fig. 9 shows G1 generator's speed deviation when a three phase short circuit fault is applied at bus 8 for 10 cycles (166.7ms). These results show that the WAM has learnt the dynamics of the two-area power system. Similarly, good estimation results are seen for other natural disturbances at various operating points.

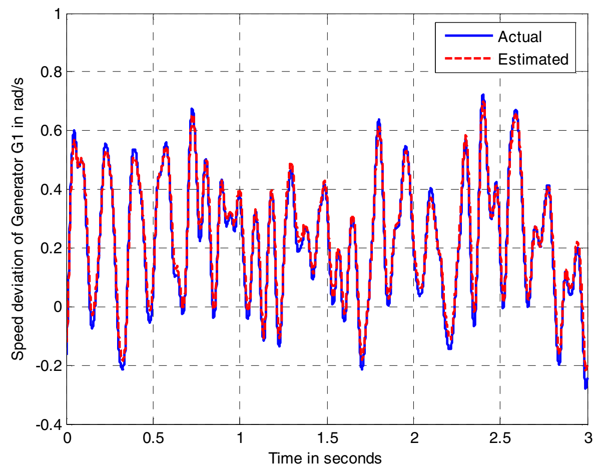

Figure 7. WAM estimated and actual speed deviation of generator G1 for PRBS applied to generators G1 and G3

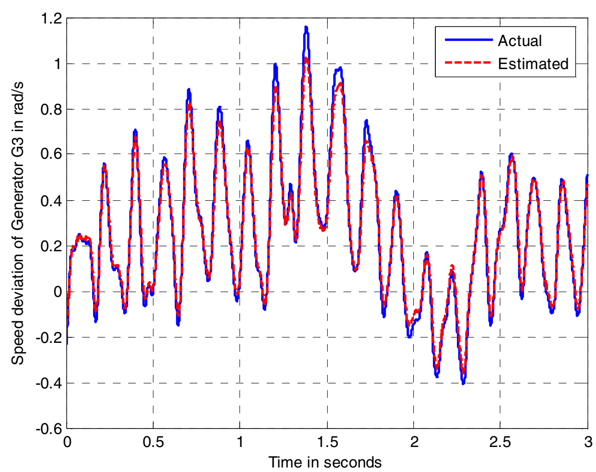

Figure 8. WAM estimated and actual speed deviation of generator G3 for PRBS applied to generators G1 and G3

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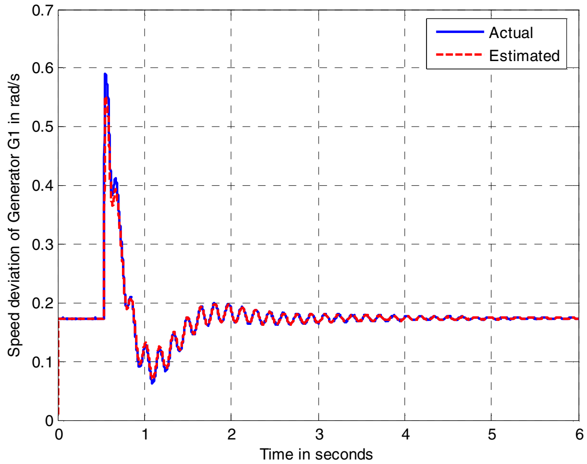

Figure 9. WAM estimated and actual speed deviation of generator G1 for a three phase short circuit applied at bus 8 (Fig. 1) for 10 cycles (166.7 ms)

B. Wide Area Controller (WAC)

Like the WAM, the training of the WAC consists of forced training and natural training [6, 7, 9]. Typical forced training results during the first 15 seconds of the desired and WAC outputs are shown in Figs. 10 and 11 for generators G1 and G3 respectively. The red dashed line shows the output signal of the WAC and the blue solid line shows the desired control signal. PRBS signals are once again applied to the excitation systems of generators G1 and G3. For the WAC training, the critic network is trained with the utility functions given in (4) and (5) for generators G1 and G3 respectively.

$$u_{G1}(t) = [4\Delta\omega_1(t) + 4\Delta\omega_1(t-1) + 16\Delta\omega_1(t-2)]^2 \qquad (4)$$

$$u_{G3}(t) = [4\Delta\omega_3(t) + 4\Delta\omega_3(t-1) + 16\Delta\omega_3(t-2)]^2 \qquad (5)$$

Once the WAC training results are satisfactory, the WAC's neural network weights are fixed and the power system is subjected to different type of disturbances. Figs. 12 and 13 show the speed devaitions of generators G1 and G3 of the two-area power system with no PSS (Uncompensated - red dotted line), with PSS on G1 and G3 (pink dashed line), with only the WAC (blue dashed-dotted solid line) and, with WAC and PSS on G1 and G3 (black solid line). It is clear from these figures that the PSS can stablize the system. The WACS provides equally or slightly better damping than the PSSs on G1 and G3. The combination of PSSs on G1 and G3, and the wide area control signals for generators G1 and G3 (the black line) provides the fast damping of the power system oscillations.

Figs. 14 and 15 show the speed deviations of G1 and G3 for one of the parallel transmission line outage between buses 7 and 8. It can be observed that the PSS, WAC and the combined WAC and PSS, all stabilize the power system. The WAC and PSSs together damp out the oscillations faster. There is a small steady state error in the speed response causing a 0.08% and 0.1% change in the frequency with the WAC and the PSSs respectively. This as a result of the speed governors have a 5% droop setting.

Figs. 16 and 17 show the speed deviations of G1 and G3 for load changes in areas 1 and 2. The load in area 1 is decreased from 967-j100 MVA to 870-j90 MVA and the load in area 2 is increased from 1767 – j250 MVA to 1863 – j260 MVA. It can be observed that the PSS, the WAC and the combined WAC and PSS, all stabilize the power system. The WAC and PSSs together damp out the oscillations faster. The WAC by itself damps out the oscillations quicker than the PSSs. There is a small steady state error in the speed response causing a 0.05% and 0.07% change in the frequency with the WAC and the PSSs respectively. This is again as a result of the speed governors have a 5% droop setting.

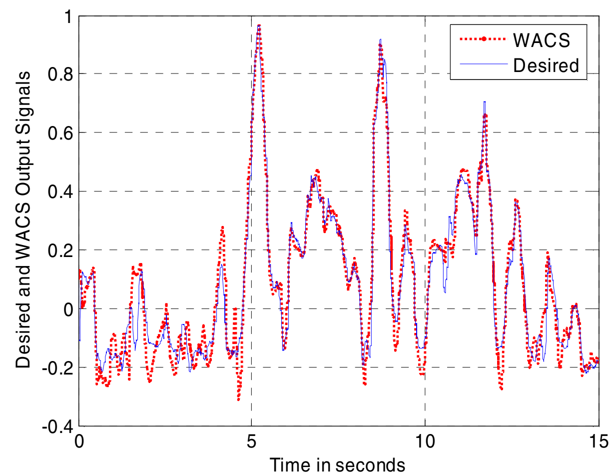

Figure 10. Desired and actual WAC output V_{w1} during forced training

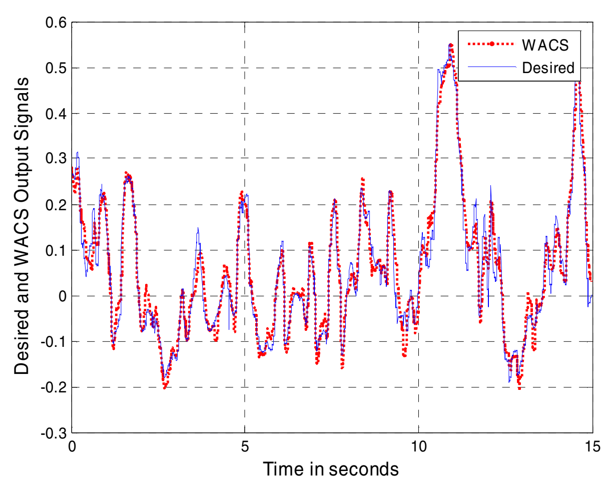

Figure 11. Desired and actual WAC output V_{w3} during forced training

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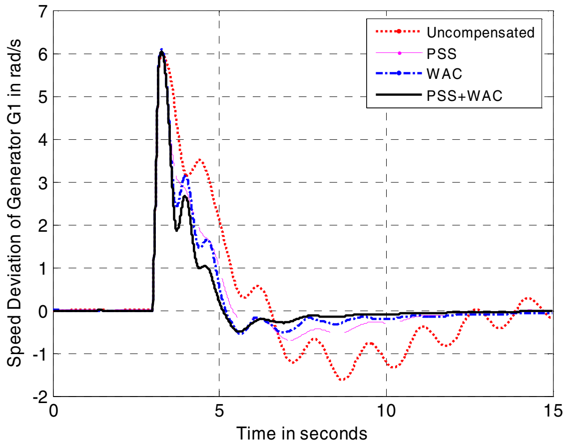

Figure 12. Speed deviation of generator G1 for different controller combination for a three phase short circuit at bus 8 (Fig. 1) for 10 cycles (166.67ms)

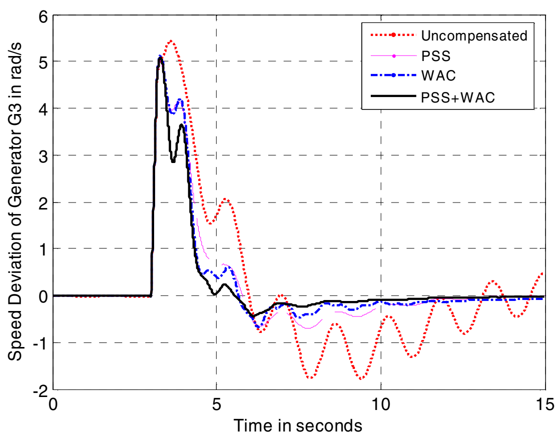

Figure 13. Speed deviation of generator G3 for different controller combination for a three phase short circuit at bus 8 (Fig. 1) for 10 cycles (166.67ms)

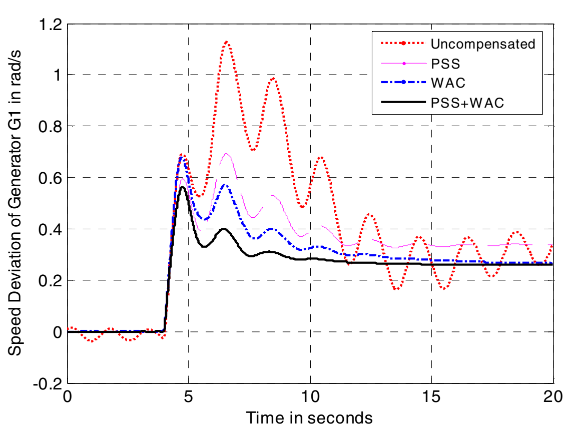

Figure 14. Speed deviation of generator G1 for different controller combination for one of the parallel tranmission line outage between buses 7 and 8 (Fig. 1)

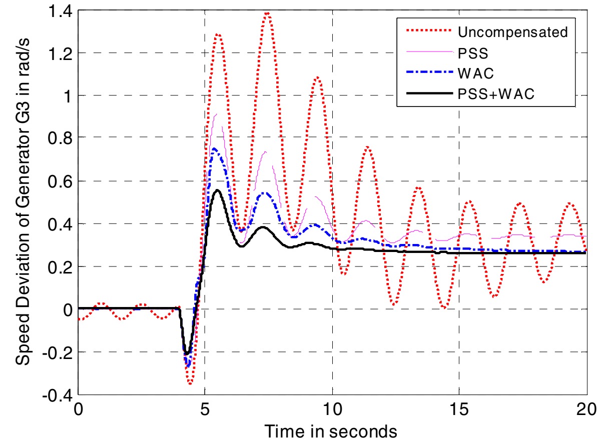

Figure 15. Speed deviation of generator G3 for different controller combination for one of the parallel tranmission line outage between buses 7 and 8 (Fig. 1)

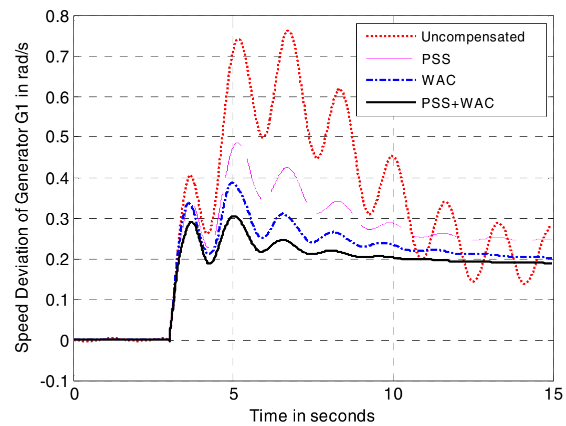

Figure 16. Speed deviation of generator G1 for different controller combination for a load decrease in area 1 and an increase in area 2 (Fig. 1)

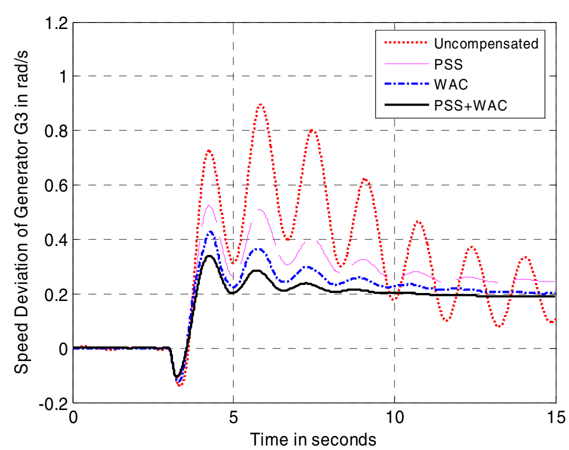

Figure 17. Speed deviation of generator G3 for different controller combination for a load decrease in area 1 and an increase in area 2 (Fig. 1)

VI. CONCLUSION

The paper has presented the design and real-time DSP implementation of an optimal wide area control system for a power system using adaptive critic designs and neural networks. The power system dynamics is estimated online by a wide area monitor using a feedforward neural network accurately and is in turn used to train another neural network to provide nonlinear optimal control based on combined concepts of approximate dynamic programming and reinforcement learning.

The WACS together with the power system stabilizers provides superior damping of system oscillations caused by small and large disturbances over a wide range of operating conditions. In addition, the DSP implementation of the WACS for the two area power system simulated on the real time digital simulator has demonstrated that it is possible for such a wide area control system to be implemented as a power system stability agent in practice to control the real world power system. Future work will involve extending the power system stability agent to FACTS devices.

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APPENDIX

Synchronous Generators (identical):

Xd = 1.8 pu, Xq = 1.7 pu, Xl = 0.2 pu, Xd' = 0.3 pu, Xq'=0.55 pu
Xd" = 0.25 pu, Xq" = 0.25 pu, Ra = 0.0025 pu
H = 6.5s (for G1 and G2) and H = 6.175s (for G3 and G4)

Operating Points of the Power System:

G1: P = 700MW, Q = 185MVar, Vt = $1.03\angle 20.2°$
G2: P = 700MW, Q = 235MVar, Vt = $1.01\angle 10.5°$
G3: P = 719MW, Q = 176MVar, Vt = $1.03\angle -6.8°$
G4: P = 700MW, Q = 202MVar, Vt = $1.01\angle -17.0°$

Load 1: P_L = 967MW, Q_L = 100MVar, Qc = 200MVar
Load 2: P_L = 1767MW, Q_L = 100MVar, Qc = 350MVar

Parameters of the PSS:

PSS: Kstab = 20, T1 = 0.05s, T2 = 0.02s, T = 10s

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