01 Aug 2008

Comparison of Adaptive Critic-Based and Classical Wide-Area Controllers for Power Systems

Swakshar Ray

Ganesh K. Venayagamoorthy
Missouri University of Science and Technology

Balarko Chaudhuri

Rajat Majumder

Recommended Citation

S. Ray et al., "Comparison of Adaptive Critic-Based and Classical Wide-Area Controllers for Power Systems," *IEEE Transactions on System, Man and Cybernetics, Part B*, Institute of Electrical and Electronics Engineers (IEEE), Aug 2008.
The definitive version is available at https://doi.org/10.1109/TSMCB.2008.924141

Comparison of Adaptive Critic-Based and Classical Wide-Area Controllers for Power Systems

Swakshar Ray, *Member, IEEE*, Ganesh Kumar Venayagamoorthy, *Senior Member, IEEE*,
Balarko Chaudhuri, *Member, IEEE*, and Rajat Majumder, *Member, IEEE*

***Abstract*—An adaptive critic design (ACD)-based damping controller is developed for a thyristor-controlled series capacitor (TCSC) installed in a power system with multiple poorly damped interarea modes. The performance of this ACD computational intelligence-based method is compared with two classical techniques, which are observer-based state-feedback (SF) control and linear matrix inequality LMI-H$^\infty$ robust control. Remote measurements are used as feedback signals to the wide-area damping controller for modulating the compensation of the TCSC. The classical methods use a linearized model of the system whereas the ACD method is purely measurement-based, leading to a nonlinear controller with fixed parameters. A comparative analysis of the controllers' performances is carried out under different disturbance scenarios. The ACD-based design has shown promising performance with very little knowledge of the system compared to classical model-based controllers. This paper also discusses the advantages and disadvantages of ACDs, SF, and LMI-H$^\infty$.**

***Index Terms*—Adaptive critics, H$^\infty$ control method, robust damping control, thyristor-controlled series capacitor (TCSC), wide-area measurements and control.**

I. INTRODUCTION

INADEQUATE damping of electromechanical oscillations has always been a concern in power systems. To address this problem, local compensators like power system stabilizers and even flexible alternating current transmission system (FACTS) devices have been installed in power systems over the years. Local controllers can provide good performance when local measurements supply all the information about the effect of disturbances. However, if there are interactions between multiple adjacent areas of the power system, a wide-area-based measurement has the potential to provide better stabilizing control [1]–[4]. The wide-area control system (WACS) coordinates the actions of a number of distributed agents using supervisory control and data acquisition, phasor measurement unit, or other sources providing wide-area dynamic information [5]. With GPS synchronized measurements, the signal transmission delay is negligible, and hence, WACS technology is becoming popular with time.

Multiple linear model-based adaptive and hierarchical wide-area controls for damping postdisturbance oscillations have been reported [6], [7]. Observer-based state-feedback (SF), linear matrix inequality (LMI), gain scheduling, and H$^\infty$-based damping controls have also been effectively used [8]–[10]. All these classical designs require a nominal model of the system, which might not be simple to obtain in practice with an acceptable degree of accuracy. An alternative solution is to adopt a design strategy that is solely based on available measurements.

In the field of computational intelligence, discrete nonlinear controller designs have been studied for many years. Neural network (NN)-based function approximators have been utilized for several of these intelligent control designs [11]–[13]. Adaptive critic designs (ACDs) utilize the approximation capabilities of NNs to develop optimal controllers from disturbance measurements of available system inputs and outputs. This methodology is based on the combined concepts of approximate dynamic programming and reinforcement learning [14], [15]. ACD methods yield a fixed controller structure that is comparable to other classical optimal controller designs. The primary differences are the following: 1) ACD yields a nonlinear controller, whereas classical optimal designs typically provide linear controllers and 2) classical methods rely on the linear model of the system whereas ACD can be a measurement-based design.

This paper presents the design of a wide-area measurement-based optimal damping controller for a thyristor-controlled series capacitor (TCSC) using the simplest ACD method, which is the heuristic dynamic programming (HDP). A performance comparison is also carried out with respect to an observer-based SF control and a robust classical control. Delays in wide-area monitoring signal transmissions are assumed to be negligible for both the classical and HDP controller designs in this paper.

II. TEST POWER SYSTEM

The test system used in this paper is a 16-machine 68-bus power system [6], [9], [16], shown in Fig. 1. A damping controller is designed to enhance the damping of the three critical interarea modes (0.39, 0.50, and 0.62 Hz) present in the system with the TCSC. The choice of measurement signals is based on the modal controllability, observability, and residue

---

Manuscript received July 27, 2007; revised March 18, 2008. This work was supported by the National Science Foundation under the CAREER Grant ECCS 0348221. This paper was recommended by Guest Editor F. Lewis.

S. Ray is with Quanta Technology, Raleigh, NC 27607 USA (e-mail: swakshar@gmail.com).

G. K. Venayagamoorthy is with the Real-Time Power and Intelligent Systems Laboratory and the Department of Electrical and Computer Engineering, University of Missouri at Rolla, Rolla, MO 65409 USA (e-mail: gkumar@ieee.org).

B. Chaudhuri is with the Control and Power Group, Electrical and Electronic Engineering Department, Imperial College, SW7 2AZ London, U.K. (e-mail: b.chaudhuri@imperial.ac.uk).

R. Majumder is with the Corporate Research Center, ABB, 72178 Vasteras, Sweden (e-mail: rajat.majumder@se.abb.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSMCB.2008.924141

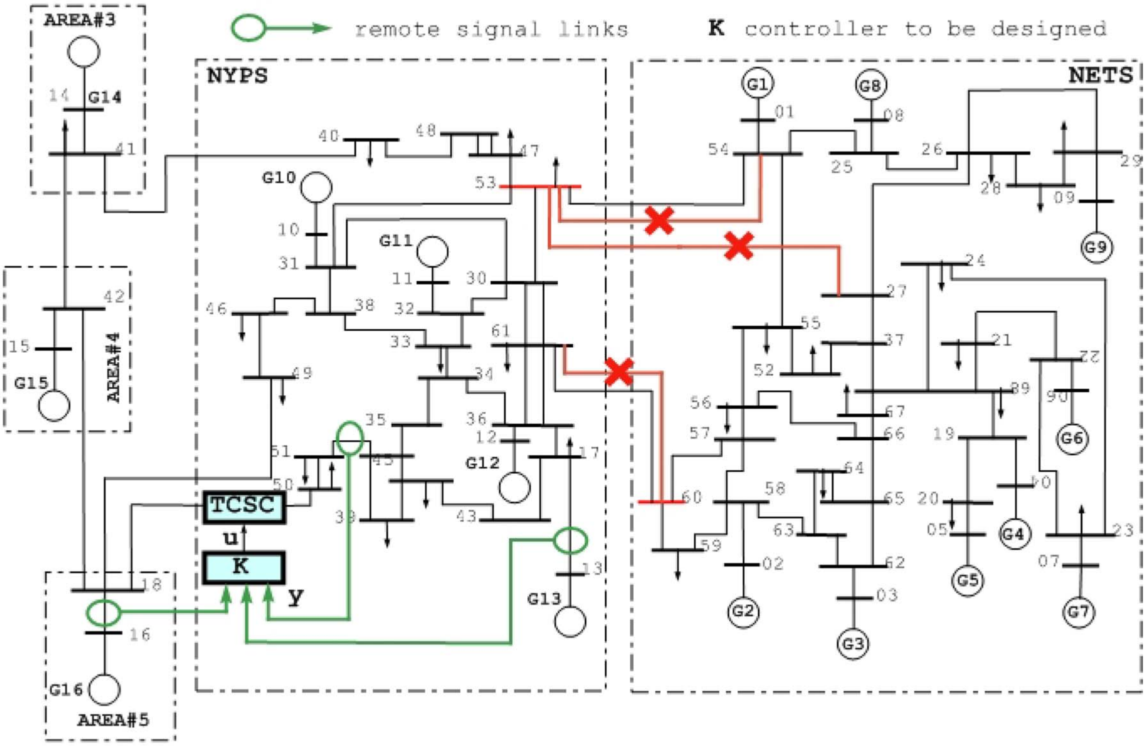


Fig. 1. New England–New York (NETS-NYPS) test power system.

analysis detailed in [16]. The highest residues were found for line flows P_{51-45}, P_{18-16}, and P_{13-17} corresponding to 0.39, 0.50, and 0.62 Hz, respectively. Hence, these measurements are used as inputs to the controller in this paper.

III. ADAPTIVE CRITICS OPTIMAL CONTROL DESIGN

ACDs are NN-based designs for optimization over time using the combined concepts of reinforcement learning and approximate dynamic programming [14], [15]. ACDs use two NNs, which are the critic and action networks, to solve the Hamilton–Jacobi–Bellman equation of optimal control. The critic network approximates the cost-to-go function J of the Bellman's equation of dynamic programming (1) and is referred to as the HDP approach in ACDs

$$J(t) = \sum_{k=1}^{\infty} \gamma^k U(t+k) \tag{1}$$

where γ is a discount factor between zero and one and $U(t)$ is a utility function or a local performance index. The action network provides optimal control to minimize or maximize the cost-to-go function J. It is referred to as the HDP neurocontroller in this paper, providing the optimal damping control signal to the TCSC. Other powerful ACD approaches that include the dual-heuristic programming (DHP) and the global dual-heuristic programming (GDHP) exist [14]. DHP critic approximates the derivatives of the cost-to-go function J with respect to the measured states whereas the GDHP critic approximates both J and the derivatives of J. The HDP damping controller design is shown in Fig. 2. More details on HDP can be found in [14] and [15]. Only the HDP critic design is illustrated in this paper.

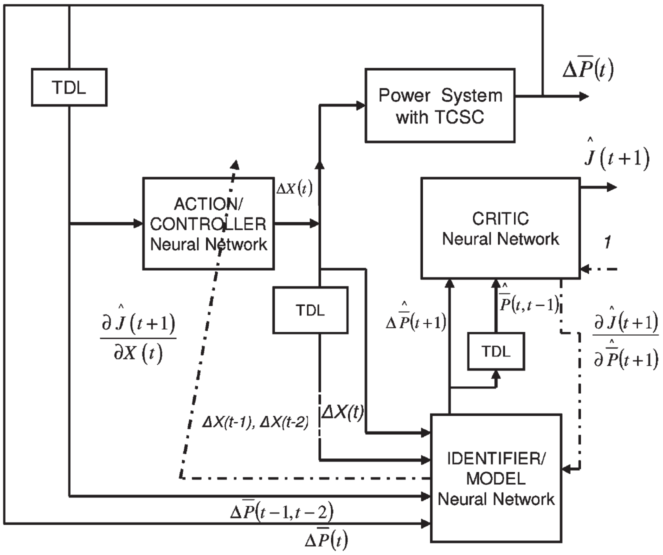


Fig. 2. HDP optimal neurocontroller design (TDL is time delay lines).

The critic network approximates the cost-to-go function J in (1). The critic network is trained forward in time, which is of great importance for real-time optimal control operation. The ability to foresee future costs and take preventive action ahead of time is important in optimal controller designs. The critic network can be seen as a future performance evaluator. The ACD techniques use NN as approximating tool to provide an alternative approach to the classical optimal control design. Inherently, both classical and ACD-based designs are similar, as shown in [15]. The target for the critic during training period is derived in (2) from (1).

$$\begin{aligned} J(t) &= \sum_{k=0}^{\infty} \gamma^k U(t+k) \\ &= U(t) + \sum_{k=1}^{\infty} \gamma^k U(t+k) \\ &= U(t) + \gamma \sum_{k=0}^{\infty} \gamma^k U\left((t+1)+k\right) \\ &= U(t) + \gamma J(t+1). \end{aligned} \tag{2}$$

In the training of the critic, the objective is to minimize

$$\sum_{t=0}^{\infty} E^2(t) \tag{3}$$

where

$$E(t) = \gamma \hat{J}\left((t+1)\right) + U\left((t) - \hat{J}(t)\right). \tag{4}$$

Here, $\hat{J}(t)$ is the estimated cost-to-go $J(t)$ evaluated by the critic network at time t and $U(t)$ is the local cost function. The particle swarm optimization (PSO) algorithm is used to minimize (3). A detailed explanation for the derivation of the utility function is given in [16]. This utility function U in (1), (2), and (4) is typically a quadratic function similar to the objective function in classical optimal control design. It plays an important role to form the user-defined optimal cost-to-go function J and is selected to give the best tradeoff between performance and the control effort. As the motivation for this design is to damp observable modes in the measured power signals, a quadratic formulation of power deviations (ΔP_{51-45}, ΔP_{18-16}, and ΔP_{13-17}) is chosen as utility function given by $\Delta(t) = \sum_{i-1}^{3} \Delta P_1^2$.

The critic network in Fig. 2 is a three-layer feedforward network with 10 input linear neurons, 15 sigmoidal neurons in the hidden layer, and 1 output linear neuron. The critic design is the key to different types of ACD techniques. In the HDP technique, the critic inputs are the neuroidentifier outputs and their two delayed values. In vector format, it is represented as $\hat{\overline{P}}(t)$, $\hat{\overline{P}}(t-1)$, and $\hat{\overline{P}}(t-2)$ (Fig. 2). The critic or performance evaluator's output is the cost-to-go function $\hat{J}(t)$. The neuroidentifier and controller designs are similar to many published works on ACD controller designs [14], [15] and has not been elaborated in this paper. Neuroidentifier, critic, and controller neural networks are initially trained offline using PSO on the measured disturbance data [17]–[19].

IV. RESULTS

Classical and adaptive critic-based damping controllers are implemented in the MATLAB/SIMULINK environment for the test system with a TCSC, as elaborated in Section II. The three critical interarea modes of the system have been found to be adequately damped for different contingencies using the classical observer-based SF controller, robust controller, and the ACD-based optimal neurocontroller. In this system, the interarea oscillations are predominantly excited for a few contingencies as specified in [10]. Simulation results corresponding to the following contingencies are presented.

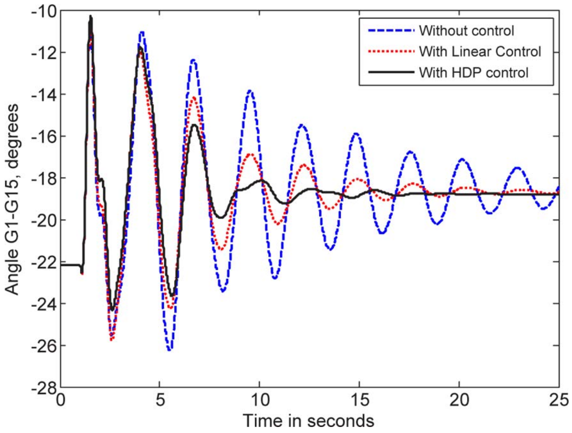


Fig. 3. Oscillation in the angle difference between G1 and G15 for contingency 2 with state feedback and HDP controllers.

1) Contingency 1 (CG1): A 3-Φ line to ground fault for 80 ms at bus 60 with an autoreclosure;
2) Contingency 2 (CG2): A 3-Φ line to ground fault at bus 53 for 80 ms and cleared by permanently opening lines 27–53 thereby changing the postfault topology of the power system.

A brief description of the two classical controller designs are provided in the following sections along with the comparison results with the ACD damping controller.

A. *Observer-Based SF Controller*

The observer-based SF controller is designed by using the pole-placement method. A linear model of 132 states of the system is derived from the nonlinear equations. The model is reduced by using balance truncation to obtain a tenth-order model. As the system states are not measurable, a state observer is designed to predict the individual states for SF controller. The desired pole locations of the state observer is set to five times the closed-loop pole of the reduced system. The real part of the desired closed-loop poles is ideally selected to provide a damping ratio of 0.2 for all interarea modes. The state-observer and SF controller gains are obtained using the "place" command in MATLAB. The performances of the linear SF and HDP controllers are shown in Figs. 3 and 4 for contingency 2.

B. *LMI-H^{∞} Robust Control Design*

The control formulation in the H^{∞} framework is shown in Fig. 5 where the notations represent the following:

$G(s)$	linearized model of the power system including the FACTS device at nominal operating condition (dotted box) with the standard connectivity between state matrix (A) and the input (B) and output (C) matrices;
$K(s)$	damping controller to be designed;
y	measured output(s); power flow in the three lines (see Section II);

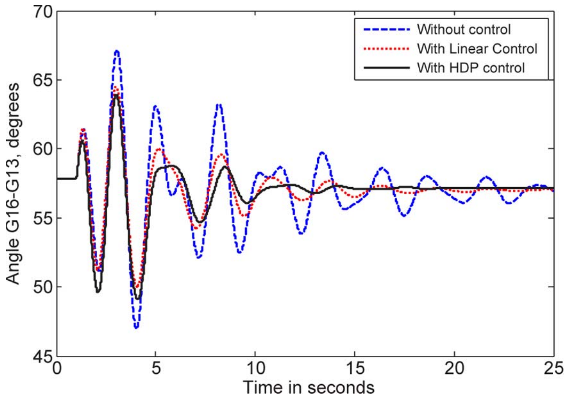


Fig. 4. Oscillation in the angle difference between G16 and G13 for contingency 2 with state feedback and HDP controllers.

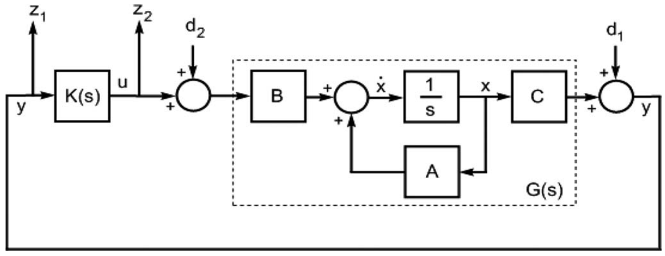


Fig. 5. Robust control design formulation.

u	control input; change in percentage compensation of TCSC over the steady state value (50%);
d_1	exogenous disturbances at the system output;
d_2	exogenous disturbances at the control input;
z_1, z_2	exogenous outputs (measures of the effect of disturbances).

The basic idea behind a robust controller design is to ensure that the effect of exogenous disturbances on the exogenous outputs should be "minimum," i.e., the controller $K(s)$ should be able to minimize the impact of disturbances d_1 and d_2 on z_1 and z_2, respectively. The transfer functions between them are given by the following:

$$\frac{z_1}{d_1} = (1 - GK)^{-1} = S \tag{5}$$

$$\frac{z_1}{d_2} = (1 - GK)^{-1}G = SG \tag{6}$$

$$\frac{z_2}{d_1} = K(1 - GK)^{-1} = KS \tag{7}$$

$$\frac{z_2}{d_2} = K(1 - GK)^{-1}G = KSG \tag{8}$$

where S is the sensitivity. The design objective is to come up with such a $K(s)$ that minimizes the infinity norm of these transfer functions. In other words, the problem is to find a $K \in S$ such that γ is minimized, satisfying the following condition:

$$\left\| \begin{bmatrix} S & KS \\ SG & KSG \end{bmatrix} \right\|_{\infty} < \gamma \tag{9}$$

where S is a set of stable controllers.

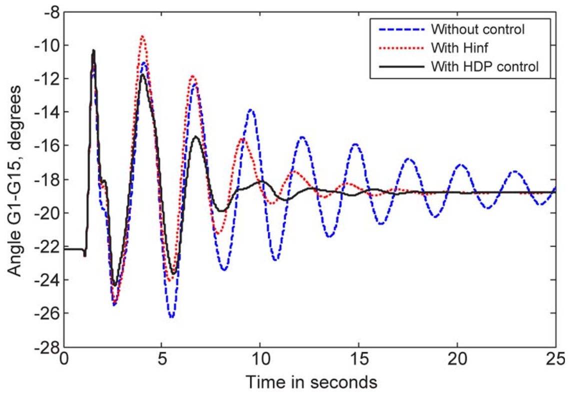


Fig. 6. Oscillation in the angle difference between G1 and G15 for contingency 2 with H^{∞} and HDP controllers.

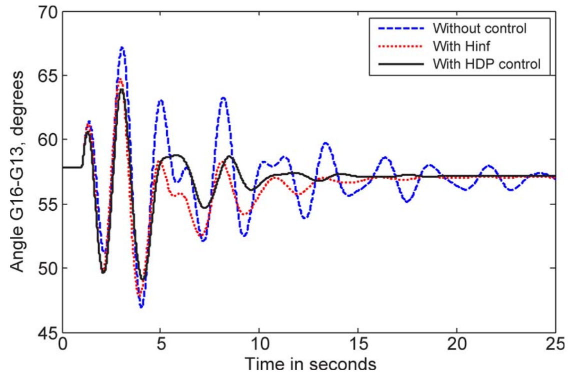


Fig. 7. Oscillation in the angle difference between G16 and G13 for contingency 2 with H^{∞} and HDP controllers.

In addition to robustness, performance in time domain is ensured by imposing a pole-placement criterion. The optimization problem in (9) with the pole-placement constraint is solved by using the LMI toolbox available in MATLAB [9], [10].

The performance of the HDP controller is also compared with the LMI-H^{∞} controller (Hinf) for the off-nominal contingency (contingency 2) as mentioned earlier. Figs. 6 and 7 show the same responses for contingency 2. The HDP controller, with little *a priori* knowledge of the complete system model and operating scenarios, shows promising performance when compared to the classical robust controller.

C. Time-Domain Analysis of Results

The observation of time-domain simulation results show that the HDP ACD-based controller performs better in terms of overshoot and settling time in most of the disturbance scenarios than the linear observer-based SF and robust H^{∞} controllers. The choice of using any one of the methods depends on whether an accurate model of the system or less noisy measurement is available. Bar charts in Figs. 8 and 9 show maximum overshoot and settling time of generator angle oscillations with different control methods for contingency 2.

D. Eigenvalue Analysis

To substantiate the improvement in the stability of the system, closed-loop eigenvalues are calculated by using MATLAB linmod function using available data of system matrices under nominal operating conditions for all three types of controllers.

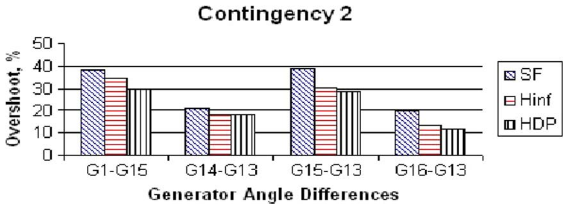


Fig. 8. Maximum overshoot in percentage for contingency 2 with different control methodologies.

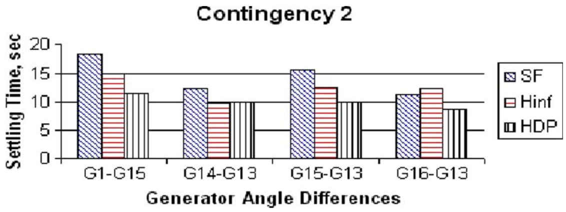


Fig. 9. Settling time for contingency 2 with different control methodologies.

TABLE I
CLOSED-LOOP FREQUENCIES AND DAMPING FOR DIFFERENT CONTROLLERS

State Feedback		H^∞		HDP	
Freq. (Hz)	Damping Ratio	Freq. (Hz)	Damping Ratio	Freq. (Hz)	Damping Ratio
0.3948	0.1617	0.3913	0.1681	0.3720	0.2067
0.5394	0.1412	0.4964	0.1410	0.4850	0.1244
0.7435	0.0679	0.6344	0.1154	0.5898	0.1235

The frequencies and damping ratios corresponding to interarea modes are shown in Table I for different controllers. The open loop frequencies and corresponding damping ratios of the original system with a TCSC under nominal operating conditions are 0.3913, 0.5080, and 0.6232 Hz and 0.0626, 0.0435, and 0.0554, respectively.

V. DISCUSSION

The classical controllers are designed by using a linear model of the system around a nominal operating point. The advantages and disadvantages of the two classical control methods and the ACD-based control method are discussed in this section.

A. Observer-Based SF Controller Design

The observer-based SF controller is a widely accepted method for linear multivariable control design. There are a number of advantages and disadvantages of this approach as listed next.

Advantages:

1) A number of techniques can be used for design including eigenvalue sensitivity, frequency domain analysis, and pole-placement methods.
2) Linear optimal controls like linear quadratic regulation or linear quadratic Gaussian technique use a closed form solution, and hence, it is easy to develop an optimal controller for a limited operating region.
3) With accurate state estimation, the SF controller is very effective within the limited region of operation.

Disadvantages:

1) An accurate linear model of the system, which is difficult to obtain for practical systems, is required.
2) As most of the system states are not measurable, the controller performance is heavily dependent on the performance of the observer/state estimator.
3) For guaranteed performance, operating regions and disturbances are limited to the neighborhood of some nominal operating condition.

B. LMI-H^∞ Robust Controller Design

The H^∞ controller is an advanced design. Similar to other linear controllers, this technique also requires accurate state matrices (A, B, C, and D) from the linearized model of the system. The advantages and disadvantages of this method are given next.

Advantages:

1) It has a guaranteed robustness.
2) It allows the minimization of control efforts.
3) It is valid for a wide range of operating regions and disturbance scenarios without prior knowledge.
4) Different frequency and time domain objectives can be included in the design, like setting minimum damping ratio for closed-loop eigenvalues.

Disadvantages:

1) It is a complex design methodology.
2) An accurate linear model of the system is required.
3) The controller may contain steep differential equations that require higher sampling rate and higher computational effort for real-time implementation in digital processors.

C. Adaptive Critic Optimal Controller Design

The ACD used in this paper is a purely measurement-based technique that yields a nonlinear neurocontroller. The adaptive critic controller training can be done either online or offline, depending on the criticality of the system. Some of the advantages and disadvantages of this method are given here.

Advantages:

1) It does not require a complete model of the system or state estimators.
2) Input and output measurements of the system are sufficient to design the controller.
3) It is valid for wide operating regions and disturbances without *a priori* knowledge.

Disadvantages:

1) It depends on disturbance measurements that are not readily available.
2) Ambient measurements can be used but noisy measurements require extra attention.
3) The initial design phase requires higher computational effort and some heuristics (NN size and learning rate).

This comparison shows that any of these presented methods can provide enhanced stability if the requirements of the design are met. Overall, the LMI-H^∞ and HDP control are more robust for wider operating regions and contingencies.

VI. CONCLUSION

This paper has presented the development of an adaptive critic-based optimal wide-area controller for damping interarea oscillations in power systems. Two classical control approaches, the SF and LMI-H^{∞} methods, which are essentially model-based techniques, are also presented for the wide-area controller design. The HDP-based neurocontroller is designed offline using PSO from the measured disturbance data of the system around the nominal operating condition. The performance comparison of the ACD controller with respect to the two well-accepted classical designs shows the promise of the proposed method. If disturbance and ambient measurement data are available for a given system, an ACD controller can provide superior performance with minimum *a priori* knowledge of system states and operating regions. This study provides a basis for considering the computational intelligence-based techniques along with the existing classical designs for developing a more advanced control and an effective one for power systems.

REFERENCES

[1] H. Ni and G. T. Heydt, "Power system stability agents using robust wide area control," *IEEE Trans. Power Syst.*, vol. 17, no. 4, pp. 1123–1131, Nov. 2002.

[2] C. W. Taylor, D. C. Erickson, K. E. Martin, R. E. Wilson, and V. Venkatasubramanian, "WACS-wide area stability and voltage control system: R & D and online demonstration," *Proc. IEEE*, vol. 93, no. 5, pp. 892–906, May 2005.

[3] I. Kamwa and R. Grondin, "PMU configuration for system dynamic performance measurement in large, multiarea power systems," *IEEE Trans. Power Syst.*, vol. 17, no. 2, pp. 385–394, May 2002.

[4] M. E. Aboul-Ela, A. A. Sallam, J. D. McCalley, and A. A. Fouad, "Damping controller design for power system oscillations using global signals," *IEEE Trans. Power Syst.*, vol. 11, no. 2, pp. 767–773, May 1996.

[5] M. Zima, M. Larsson, P. Korba, C. Rehtanz, and G. Andersson, "Design aspects for wide-area monitoring and control systems," *Proc. IEEE*, vol. 93, no. 5, pp. 980–996, May 2005.

[6] B. Chaudhuri, R. Majumder, and B. C. Pal, "Application of multiple-model adaptive control strategy for robust damping of interarea oscillations in power system," *IEEE Trans. Control Syst. Technol.*, vol. 12, no. 5, pp. 727–736, Sep. 2004.

[7] F. Okou, L.-A. Dessaint, and O. Akhrif, "Power systems stability enhancement using a wide-area signals based hierarchical controller," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1465–1477, Aug. 2005.

[8] A. Elices, L. Rouco, H. Bourles, and T. Margotin, "Physical interpretation of state feedback controllers to damp power system oscillations," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 436–443, Feb. 2004.

[9] B. Chaudhuri and B. C. Pal, "Robust damping of multiple swing modes employing global stabilizing signals with a TCSC," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 499–506, Feb. 2004.

[10] R. Majumder, B. Chaudhuri, H. El-Zobaidi, B. C. Pal, and I. M. Jaimoukha, "LMI approach to normalized H-infinity loop-shaping design of power system damping controllers," *Proc. Inst. Electr. Eng.—Gen., Transm., Distrib.*, vol. 152, no. 6, pp. 952–960, Nov. 2005.

[11] K. S. Narendra and K. Parthasarathy, "Identification and control of dynamical systems using neural networks," *IEEE Trans. Neural Netw.*, vol. 1, no. 1, pp. 4–27, Mar. 1990.

[12] J.-W. Park, R. G. Harley, and G. K. Venayagamoorthy, "MLP/RBF neural-networks-based online global model identification of synchronous generator," *IEEE Trans. Ind. Electron.*, vol. 52, no. 6, pp. 1685–1695, Dec. 2005.

[13] G. K. Venayagamoorthy and R. G. Harley, "Two separate continually online-trained neurocontrollers for excitation and turbine control of a turbogenerator," *IEEE Trans. Ind. Appl.*, vol. 38, no. 3, pp. 887–893, May/Jun. 2002.

[14] J. Si, A. Barto, W. Powell, and D. C. Wunsch, *Handbook of Learning and Approximate Dynamic Programming*. New York: Wiley, Jul. 2004.

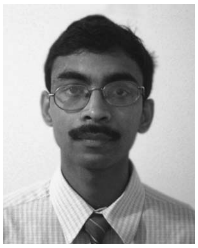
[15] J.-W. Park, R. G. Harley, and G. K. Venayagamoorthy, "Adaptive-critic-based optimal neurocontrol for synchronous generators in a power system using MLP/RBF neural networks," *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1529–1540, Sep./Oct. 2003.

[16] B. C. Pal and B. Chaudhuri, *Robust Control in Power Systems*. New York: Springer-Verlag, 2005.

[17] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. IEEE Int. Conf. Neural Netw.*, Australia, vol. 4, pp. 1942–1948.

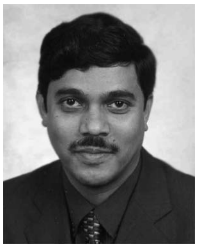
[18] Y. del Valle, G. K. Venayagamoorthy, S. Mohagheghi, J.-C. Hernandez, and R. G. Harley, "Particle swarm optimization: Basic concepts, variants and applications in power system," *IEEE Trans. Evol. Comput.*, vol. 12, no. 2, pp. 171–195, Apr. 2008.

[19] V. G. Gudise and G. K. Venayagamoorthy, "Comparison of particle swarm optimization and backpropagation as training algorithms for neural networks," in *Proc. IEEE Swarm Intell. Symp.*, Apr. 2003, pp. 110–117.



Swakshar Ray (S'02–M'08) received the B.E. degree with first-class honors in electrical engineering from the Jadavpur University, Calcutta, India, the M.S. degree in electrical engineering from Oklahoma State University, Stillwater, in 2000 and 2003, respectively, and the Ph.D. degree from the University of Missouri, Rolla, in 2007.

He was a Commissioning Engineer with the Control and Automation Division, Larsen and Toubro India Ltd., Mumbai, India, from August 2000 to December 2001. Currently, he is a Senior Engineer with Quanta Technology, Raleigh, NC (a power consulting group).



Ganesh Kumar Venayagamoorthy (S'91–M'97–SM'02) received the B.Eng. degree (with first-class honors) in electrical and electronics engineering from Abubakar Tafawa Balewa University, Bauchi, Nigeria, in 1994, and the M.Sc.Eng. and Ph.D. degrees in electrical engineering from the University of Natal, Durban, South Africa, in 1999 and 2002, respectively.

He is currently an Associate Professor of Electrical and Computer Engineering and the Director of the Real-Time Power and Intelligent Systems Laboratory, University of Missouri, Rolla. He has published over 260 refereed technical articles in journals and conference proceedings and attracted in the excess of U.S. $4 million in competitive research funding. His research interests are in the development and applications of computational intelligence techniques for power systems control and stability.

Dr. Venayagamoorthy is the recipient of several awards including the IEEE Power Engineering Society Walter Fee Award, the 2004 National Science Foundation, USA CAREER Award, and the 2007 U.S. Office of Naval Research Young Investigator Program Award.

Balarko Chaudhuri (S'02–M'06) received the Ph.D. degree from Imperial College, London, U.K., in 2005.

He was with GE Global Research from 2005 to 2006. Currently, he is a Lecturer with the Control and Power Group, Electrical and Electronic Engineering Department, Imperial College. His research interests are power system dynamics, stability, and control.

Rajat Majumder (M'03) received the B.E. degree (first class honors) in electrical engineering from the Jadavpur University, Calcutta, India, the M.Sc. degree in electrical engineering from the Indian Institute of Science, Bangalore, India, in 2000 and 2003, respectively, and the Ph.D. degree from Imperial College, London, U.K., in 2006.

Currently, he is a Scientist with the Corporate Research Center, ABB, Vasteras, Sweden. He was a Lecturer with the University of Queensland, Brisbane, Australia, from 2005 to 2007.