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Stability and Voltage Regulation Enhancement Using an Optimal Gain Vector

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***Abstract*--This paper addresses a control methodology to enhance stability and voltage regulation for the existing power systems with conventional PSS and AVR equipments. The control design problem is reduced to find a new control loop including a simple fixed gain vector. In order to optimal tuning of gain elements, the problem is formulated via an H_∞ static output feedback (H_∞ -SOF) control technique, and the solution is easily carried out using a developed iterative linear matrix inequalities (ILMI) algorithm. A single-machine infinite-bus system example is given to illustrate the developed approach. The results of the proposed control strategy are compared with conventional PSS design. The robust controller is shown to maintain the robust performance and minimize the effect of disturbance properly.**

***Index Terms*— Power system stabilizer, voltage regulation, H_∞ control, static output feedback control, robust performance, LMI.**

I. Introduction

Power systems continuously experience changes in operating conditions due to variations in generation/load and a wide range of disturbances [1]. Power system stability and voltage regulation have been considered as an important problem for secure system operation over the years. Currently, because of expanding physical setups, functionality and complexity of power systems, the mentioned problem becomes a more significant than the past. That is why in recent years a great deal of attention has been paid to application of advanced control techniques in power system as one of the more promising application areas.

On the other hand, the real-world power systems still use the simple controllers that their parameters are usually tuned based on classical, experiences and trial-and-error approaches. Although these controllers are incapable to obtain good dynamical performance for a wide range of operating conditions and disturbances, however, the real electric industry because of some probable risks, bugs and/or having a complex structure is too conservative to open the conventional control loops and test the proposed advanced controllers.

Since the (transient) stability and voltage regulation are ascribed to different model descriptions, some recent proposed scenarios [2-4] apply a switching strategy of two different kinds of controller to cover the different behavior of system operation during transient period and post-transient period. The performance of these schemes essentially depends upon the selection of switching time. Moreover, using different control surfaces through a highly nonlinear structure increases the complexity of designed controllers.

This paper presents a methodology to enhance the stability and voltage regulation of existing power system without opening their conventional PSS and AVR devices. The methodology provides a simple vector gain in parallel with the conventional control devices. The design objectives are formulated via an H∞ static output feedback (H∞-SOF) control problem and the optimal static gains are obtained using a developed iterative linear matrix inequalities (ILMI) algorithm.

The resulting control framework is not only robust but it also allows direct and effective trade-off between voltage regulation and damping performance. The proposed controller uses the well available measure signals and has merely proportional gains; so gives considerable promise for implementation, especially in a multi-machine system. In fact the proposed control strategy attempts to make a bridge between the simplicity of control structure and robustness of stability and performance to satisfy the simultaneous AVR and PSS tasks. The proposed strategy is applied to a single-machine infinite-bus system. To show the effectiveness of this methodology, the results of the proposed control approach are compared with the power system with conventional PSS and AVR devices.

II. Proposed Control Strategy

A. A Background on H_∞ Based SOF Control Design

This section gives a brief overview of H_∞ based SOF control. Consider a linear time invariant system *G(s)* with the following state-space realization.

$$G_i(s): \begin{aligned} \dot{x}_i &= A_i x_i + B_{1_i} w_i + B_{2i} u_i \\ z_i &= C_{1i} x_i + D_{12i} u_i \\ y_i &= C_{2i} x_i \end{aligned} \qquad (1)$$

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where x_i is the state variable vector, w_i is the disturbance and area interface vector, z_i is the controlled output vector and y_i is the measured output vector.

The H∞ static output feedback (H∞-SOF) control problem for the linear time invariant system $G_i(s)$ with the state-space realization of (1) is to find a gain matrix K_i ($u_i = K_i y_i$), such that the resulted closed-loop system is internally stable, and the H∞ norm from w_i to z_i (Fig. 1) is smaller than γ , a specified positive number, i.e.

$$\left\| T_{z_i w_i}(s) \right\|_\infty < \gamma \tag{2}$$

It is notable that the H∞-SOF control problem can be transferred to a generalized SOF stabilization problem which is expressed via the following theorem.

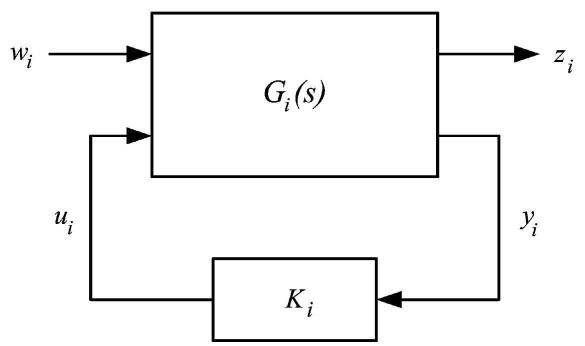


Fig. 1. Closed-loop system via H∞-SOF control

<u>*Theorem.*</u> The system (*A, B, C*) that may also be identified by the state-space model,

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{3}$$

is stabilizable via SOF if and only if there exist $P>0$, $X>0$ and K_i satisfying the following quadratic matrix inequality

$$\begin{bmatrix} A^T X + XA \text{ - } PBB^T X - XBB^T P + PBB^T P & (B^T X + K_i C)^T \\ B^T X + K_i C & -I \end{bmatrix} < 0 \tag{4}$$

Since a solution for the consequent non convex optimization problem (4) can not be directly achieved by using general LMI technique [5], a variety of methods were proposed by many researchers with many analytical and numerical methods to approach a local/global solution. In this paper, to solve the resulted SOF problem, an iterative LMI (ILMI) is used based on the given necessary and sufficient condition for SOF stabilization in [6], via the H∞ control technique.

B. Proposed Control Framework

The overall control structure using SOF control design for an assumed power system is shown in Fig. 2, where blocks PSS and AVR represents the existing conventional power system stabilizer and voltage regulators. Here the electrical power signal Δp_{ei} is considered as input signal for the PSS unit. The optimal gain vector uses the terminal voltage Δv_{ti} , electrical power Δp_{ei} and machine speed $\Delta\omega_i$ as input signals. Δv_{refi} and d_i show the reference voltage deviation and system disturbance input, respectively.

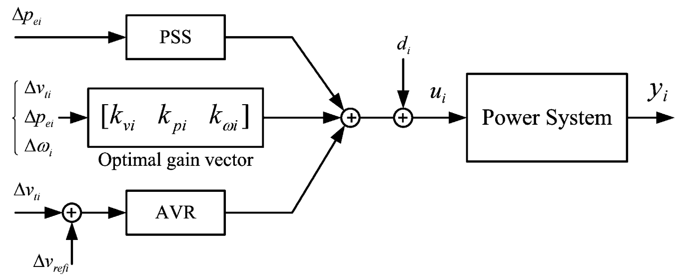


Fig. 2. Overall control structure

Using linearized model for a given power system unit "*i*" in the form of (1) and performing the standard H∞-SOF configuration (Fig. 1) with considering an appropriate controlled output signals results an effective control framework, which is shown in Fig. 3. This control structure adapts the H∞-SOF control technique with the described power system control targets and allows direct trade-off between voltage regulation and closed-loop stability by merely tuning of a vector gain.

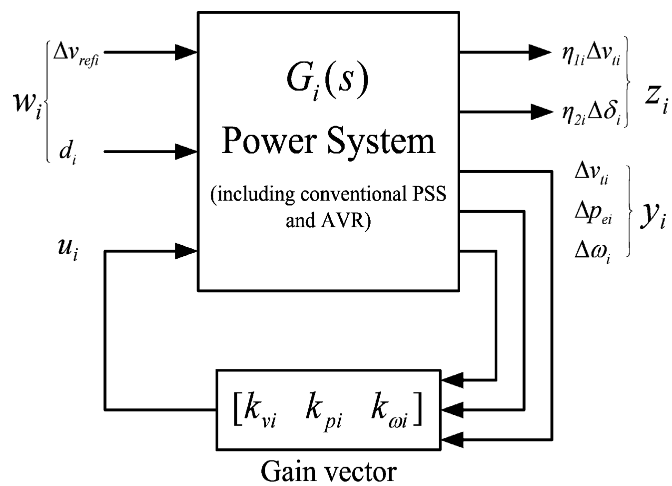


Fig. 3. The proposed H∞-SOF control framework

Here, disturbance input vector w_i , controlled output vector z_i and measured output vector y_i are considered as follows:

$$w_i^T = \left[\Delta v_{refi} \quad d_i\right] \tag{5}$$

$$z_i^T = [\eta_{1i}\Delta v_{ti} \quad \eta_{2i}\Delta\delta_i] \tag{6}$$

$$y_i^T = \left[\Delta v_{ti} \quad \Delta p_{ei} \quad \Delta\omega_i\right] \tag{7}$$

where η_{1i}, η_{2i} are constant weights that must be chosen by designer to get the desired closed-loop performance. The selection of performance constant weights η_{1i} and η_{2i} is dependent on the specified performance objectives. In fact an important issue with regard to selection of these weights is the degree to which they can guarantee the satisfaction of design performance objectives. The selection of these weights entails a trade off among several performance requirements.

Since the vector z_i properly covers the significant controlled signals which must be minimized by an ideal AVR-PSS design, it is expected that the proposed robust controller to be able to coordinate the voltage regulation and stabilizing objectives, properly.

C. Developed ILMI Algorithm

The proposed ILMI algorithm to solve the H∞-SOF is mainly based on the given approach in [6]. The key point is to formulate the H∞ problem via a generalized static output stabilization feedback such that all eigenvalues of (A-$B\,K_i\,C$) shift towards the left half plane through the reduction of a, a real number, to close to feasibility of (4). The described theorem in the previous section gives a family of internally stabilizing SOF gains is defined as K_{sof}. But we are looking for the solution of following optimization problem: Given an optimal performance index γ , (2), resulted from the application of H∞ dynamic output feedback control to the control area i, determine an admissible SOF law

$$u_i = K_i y_i \ , \ K_i \in K_{sof} \tag{8}$$

such that

$$\left\| T_{zi\,wi}(s) \right\|_\infty < \gamma^* \tag{9}$$

where γ^* indicates a lower bound such that the closed-loop system is H∞ stabilizable via SOF. In this case we could see that $\left|\gamma - \gamma^*\right| < \varepsilon$, where ε is a small positive number.

The proposed algorithm, which is summarized in Fig. 4, gives an iterative LMI solution for above optimization problem. Here $\overline{A}_i$, $\overline{B}_i$ and $\overline{C}_i$ are defined as follows:

$$\overline{A}_i = \begin{bmatrix} A_i & B_{1i} & 0 \\ 0 & -\gamma I/2 & 0 \\ C_{1i} & 0 & -\gamma I/2 \end{bmatrix},\ \overline{B}_i = \begin{bmatrix} B_{2i} \\ 0 \\ D_{12i} \end{bmatrix},\ \overline{C}_i = \begin{bmatrix} C_{2i} & 0 & 0 \end{bmatrix} \tag{10}$$

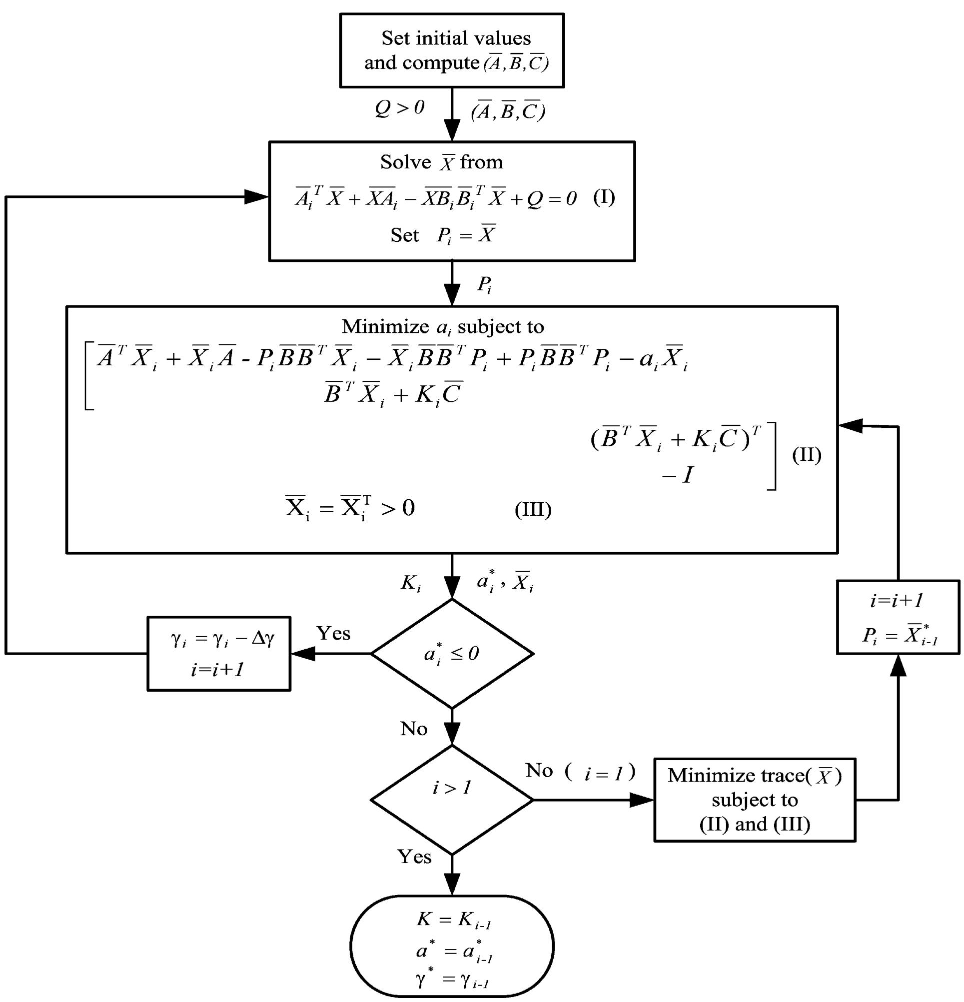


Fig. 4. ILMI algorithm.

III. Application to a Single Machine Infinite Bus System

To illustrate the effectiveness of the proposed control strategy, one-machine infinite-bus system, shown in Fig. 5, is considered as a test system. The electrical power signal is considered as the input signal of PSS. The system uses the conventional PSS, AVR and exciter system as shown in Fig. 6. Assumed constant gains and power system parameters are given in Appendix.

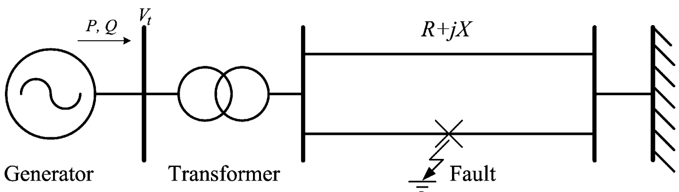
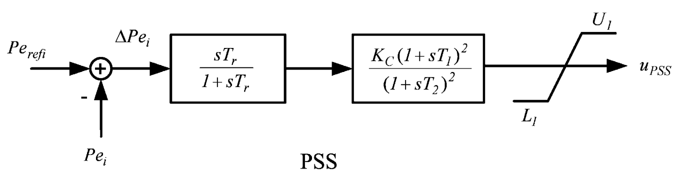
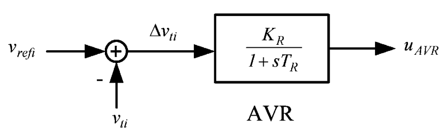


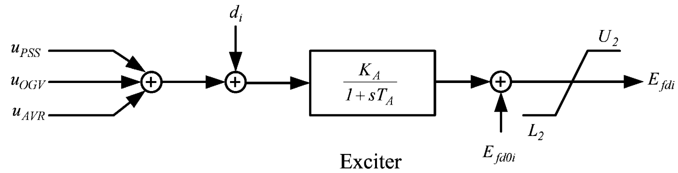
Fig. 5. Single-machine infinite-bus power system



(a)



(b)



(c)

Fig. 6. Conventional excitation control system: a) PSS, b) AVR and c) Exciter

IV. Simulation Results

In order to demonstrate the effectiveness of the proposed strategy, some nonlinear simulations were carried out. The performance of the closed-loop system in comparison of a conventional PSS and AVR is tested in the presence of voltage deviation, faults and system disturbance. For this purpose, a quite popular structure for the conventional PSS, shown in Fig. 6, is considered. Many existing generators are commissioned with a PSS of this form.

For the problem at hand, the gain and the time constants of conventional PSS are properly selected using a similar tuning procedure described in [7]. The parameters of used PSS and AVR are given in Appendix. In first test case, the performance of two controllers was evaluated in the presence of a 0.1 pu step disturbance injected at the voltage reference input of the AVR at 1 second. Fig. 7 shows the closed-loop response of the power systems fitted with the conventional control devices and the proposed gain vector.

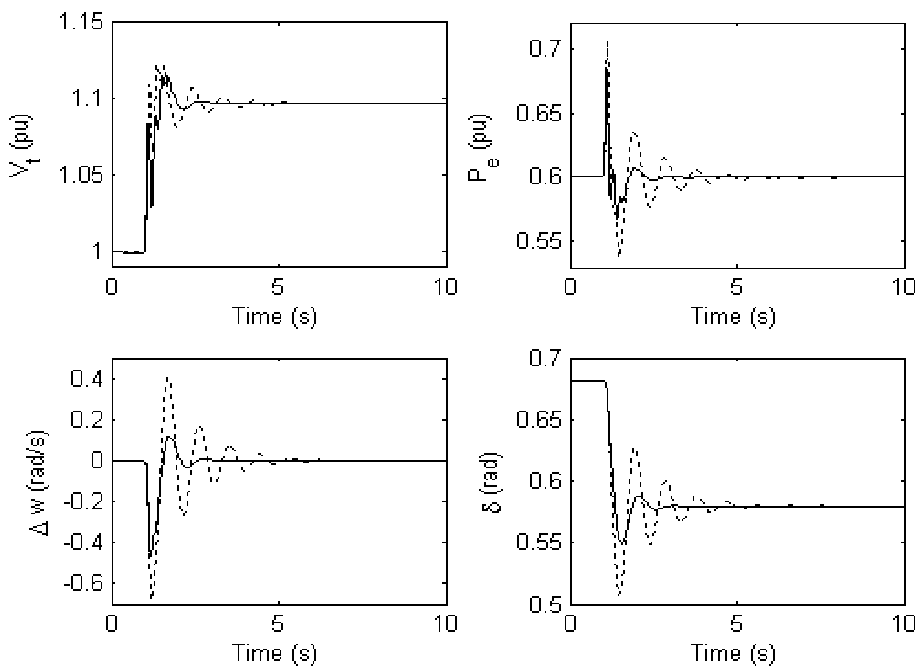


Fig. 7. System response for a 0.1 pu step change at the voltage reference input; Solid (with proposed design), dotted (only conventional PSS and AVR).

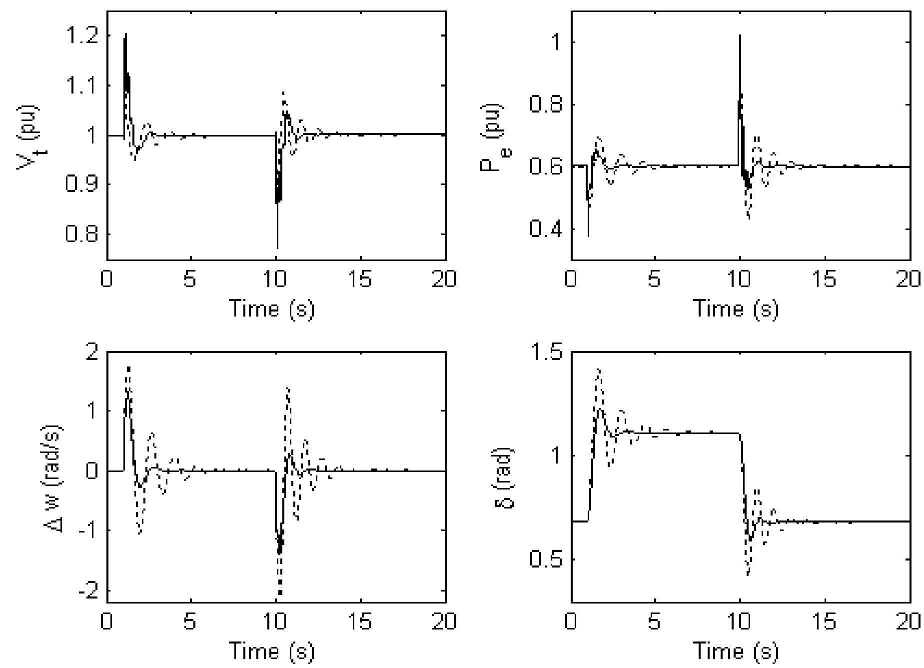


Fig. 8. System response for a fault during 1 to 10 seconds; Solid (with proposed design), dotted (only conventional PSS and AVR).

Fig. 7 shows the terminal voltage, electrical power, machine speed and angle following a fault on the related line during 1 to 10 seconds. Finally, Fig. 9 shows the system response in the face of a step disturbance in the closed-loop system.

Comparing the simulation results shows that the robust design achieves robustness against the voltage deviation, disturbance and line fault with a quite better performance with less control effort.

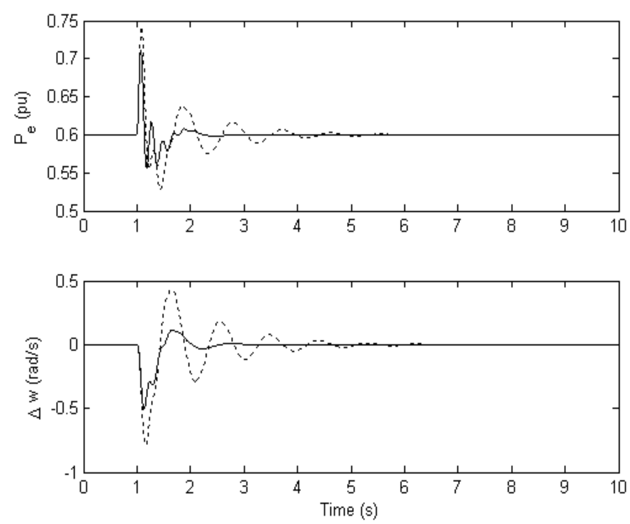


Fig. 9. System response for a step disturbance (d_i) ; Solid (with proposed design), dotted (only conventional PSS and AVR).

V. Conclusion

In order to enhancement the power system stability and voltage regulation, a new control strategy is developed using an optimal gain vector provided by H∞-SOF control technique via an ILMI algorithm. The proposed method was applied to a single-machine infinite-bus power system, and the results are compared with the conventional PSS and AVR design. The performance of the resulting closed-loop system is shown to be satisfactory over a wide range of operating conditions.

VI. References

[1] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. V. Cutsem and V. Vittal, "Definition and classification of power system stability," *IEEE Trans on Power Systems,* vol. 19, no. 2, pp. 1387-1401, 2004.

[2] Y. Wang and D. J. Hill, "Robust nonlinear coordinated control of power systems," *Automatica*, vol. 32, no. 4, pp. 611-618, 1996.

[3] Y. Guo, D. J. Hill and Y. Wang, "Global transient stability and voltage regulation for power systems," *IEEE Trans on Power Systems,* vol. 16, no. 4, pp. 678-688, 2001.

[4] N. Yadaiah, A. G. D. Kumar and J. L. Bhattacharya, "Fuzzy based coordinated controller for power system stability and voltage regulation," *Electric Power System Research*, vol. 69, pp. 169-177, 2004.

[5] S. P. Boyed, L. El Chaoui, E. Feron and V. Balakrishnan, *Linear matrix inequalities in systems and control theory* (in Studies in applied mathematics), Philadelphia, PA: SIAMA, 1994.

[6] Y. Y. Cao, J. Lam, Y. X. Sun and W. J. Mao, "Static output feedback stabilization: an ILMI approach, " *Automatica*, vol. 34, no. 12, pp. 1641-1645, 1998.

[7] E. V. Larsen and D. A. Swann, "Applying power system stabilizers parts I-III," *IEEE Trans on Power Apparat Systems*, vol.101, pp. 3017-3046, 1981.

[8] Y. Yu, *Electric power system dynamics*, Academic Press, Inc., 1983.

VII. Appendix

Power system parameters (Dimensions, notation and labels are considered the same as given in [8]):

Generator:

$x_d = 0.905,\ x'_d = 0.144,\ x_q = 0.542,\ x'_q = 0.542,$
$T_{d0} = 1.49,\ T_{q0} = 0.13$

Conventional PSS:

$K_C = 5.0,\ T_1 = 0.10,\ T_2 = 0.12$
$T_r = 3,\ U_1 = 1.0,\ L_1 = -1.0$

AVR:

$K_R/(1+sT_R);\quad K_R = 10.0,\ T_R = 0.05$

Line:

$R = 0.0269,\ X = 0.6231$

Exciter:

$K_A = 6.48,\ T_A = 0.02, U_2 = 7.6,\ L_2 = -5.2$

Initial state:

$f_0 = 60\ Hz,\ V_{t0} = 1\ pu,\ P_0 = 1\ pu$

Constant weights:

$\eta_{1i} = 0.5\ ,\ \eta_{2i} = 0.1$

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