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Simultaneous Power System Stabilizing and Voltage Regulation: A Robust Control Approach

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Abstract: *This paper addresses a robust control methodology to enhance the power system stability and voltage regulation as an integrated design approach. The automatic voltage regulation and power system stabilizer design problems are reduced to solve a single H∞-based static output feedback control problem. To determine the optimal gains, an iterative linear matrix inequalities (LMI) algorithm is used. To demonstrate the efficiency of the proposed control strategy, an experimental study has been performed for a four-machine infinite-bus system at the Research Laboratory of the Kyushu Electric Power Co. in Japan. The proposed robust technique is properly shown to maintain the robust performance and minimize the effects of disturbances.*

Keywords: H∞ control, static output feedback, LMI, voltage regulation, power system stabilizer, robust performance.

1. 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.

Conventionally, the automatic voltage regulation and power system stabilizer (AVR-PSS) design is considered as a sequential design including two separate stages. Firstly, the AVR is designed to meet the specified voltage regulation performance and then the PSS is designed to satisfy the stability and required damping performance. It is well known that the stability and voltage regulation are ascribed to different model descriptions, and it has been long recognized that AVR and PSS have inherent conflicting objectives.

In the conventional AVR-PSS [2], the PSS consisting of a gain in series with lead-lag structure, generating a stabilizing signal to modulate the reference of the AVR which is essentially a first order lag controller. The phase compensation needed is often quite large; hence it often results in the saturation of the PSS, especially if it is constructed out of analog components. Furthermore, the achievable performance of the PSS may be limited by the structure and closed-loop tuning of the AVR [3].

The conflict between voltage regulation and damping are well addressed in Ref. [3], [4] and [5]. In Ref. [3] and [4] it is analytically shown that for an ideal AVR design without any internal pre-compensation, the AVR is detrimental to the inherent system damping. A result for constant AVR gain is stated in Ref. [5]. Interested readers can refer to the mentioned references to see the analysis detail. From the performed studies, it can be deduced that the successful achievement of both goals using nonintegrated design approach turns out to be very difficult. Therefore, it is reasonable to realize a compromise between the desired stability and regulation performances by a unique controller.

In the last two decades, some studies have considered an integrated design approach to AVR and PSS design using domain partitioning [5], robust pole-replacement [6] and adaptive control [7]. Recently, some control methods have been reported on coordination of various requirements for stabilization and voltage regulation within the one controller [8-13]. A desensitized controller based on Linear Quadratic Gaussian (LQG) optimal technique is used in Ref. [8]. An approach used in Ref. [3] and [4] involves use of Internal Model Control (IMC) method to make a trade-off between voltage regulation and power system stabilization. Although all above approaches have used linear control techniques, because of complexity of control structure, numerous unknown design parameters and neglecting real constraints, they are not well suited to meet the design objectives for a multi-machine power system. Some proposed scenarios 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 [9-11]. 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. As a preliminary step of this work, the authors have addressed the problem of a robust control methodology to enhance the stability and voltage regulation of a single-machine infinite bus in the presence of conventional PSS and AVR equipments [12, 13].

In this paper, the stabilization and voltage regulation in the presence of practical constraints are formulated via an H∞ static output feedback (H∞-SOF) control problem, and then it is solved using an iterative linear matrix inequalities (LMI) algorithm. The resulting controller is not only robust but it also allows direct effective trade-off between voltage regulation and damping performance.

To demonstrate the efficiency of the proposed control method, some real time nonlinear laboratory tests have been performed on a four-machine infinite-bus system using the Analog Power System Simulator at the Research Laboratory of the Kyushu Electric Power Company (Japan). The obtained results are compared with a full-order dynamic H∞ output feedback control design.

2. H∞-SOF Control Design: A Background

This section gives a brief overview for the H∞ based static output feedback (H∞-SOF) control design. Consider a linear time invariant system $G(s)$ with the following state-space realization.

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

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 A_i, B_{1i}, B_{2i}, C_{1i}, C_{2i} and D_{12i} are known real matrices of appropriate dimensions.

The 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 is smaller than γ, a specified positive number, i.e.

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

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 [14].

Theorem. The system (*A, B, C*) is stabilizable via SOF if and only if there exist $P>0$, $X>0$ and K_i satisfying the following quadratic matrix inequality

$$\begin{bmatrix} A^T X + XA - PBB^T X - XBB^T P + PBB^T P & (B^T X + K_i C)^T \\ B^T X + K_i C & -I \end{bmatrix} < 0 \quad (3)$$

Here, the matrices A, B and C are constant and have appropriate dimensions. The X and P are symmetric and positive-definite matrices.

Since a solution for the consequent non convex optimization problem (3) cannot be directly achieved by using general LMI technique, 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 is used based on the existence necessary and sufficient condition for SOF stabilization, via the H∞ control technique.

3. Proposed Control Methodology

3.1 Modelling

In order to design a robust power system controller, it is first necessary to consider an appropriate linear mathematical description of multi-machine power system with two axis generator models. In the view point of generator unit "i", the state space representation model for such a system has the form

$$\begin{aligned} \dot{x}_{1i} &= x_{2i} \\ \dot{x}_{2i} &= -(D_i/M_i)x_{2i} - (1/M_i)\Delta P_{ei}(x) \\ \dot{x}_{3i} &= -(1/T'_{d0i})x_{3i} - (\Delta x_{di}(x)/T'_{d0i})\Delta I_{di}(x) + u_i \\ \dot{x}_{4i} &= -(1/T'_{q0i})x_{4i} - (\Delta x_{qi}(x)/T'_{q0i})\Delta I_{qi}(x) \end{aligned} \quad (4)$$

where the states

$$x_i^T = \begin{bmatrix} x_{1i} & x_{2i} & x_{3i} & x_{4i} \end{bmatrix} = \begin{bmatrix} \delta_i & \omega_i & E'_{qi} & E'_{di} \end{bmatrix} \quad (5)$$

are defined as deviation from the equilibrium values

$$x_{ei}^T = \begin{bmatrix} \delta_{1i}^e & \omega_{2i}^e & E'^e_{qi} & E'^e_{di} \end{bmatrix}$$

and, here

$$\Delta x_{di} = x_{di} - x'_{di}, \ \Delta x_{qi} = x_{qi} - x'_{di} \quad (6)$$

$$\Delta P_{ei}(x) = (E'_{di} I_{di} + E'_{qi} I_{qi}) - (E'^e_{di} I^e_{di} + E'^e_{qi} I^e_{qi}) \quad (7)$$

$$I_{di} = \sum_k [G_{ik} \cos\delta_{ik} + B_{ik} \sin\delta_{ik}] E'_{dk} + \sum_k [G_{ik} \sin\delta_{ik} - B_{ik} \cos\delta_{ik}] E'_{qk} \quad (8)$$

$$I_{qi} = \sum_k [B_{ik} \cos\delta_{ik} - G_{ik} \sin\delta_{ik}] E'_{dk} + \sum_k [G_{ik} \cos\delta_{ik} + B_{ik} \sin\delta_{ik}] E'_{qk} \quad (9)$$

A detailed description of all symbols and quantities can be found in Ref. [15]. Using the linearization technique and after some manipulation, the nonlinear state equations (5) can be expressed in the form of following linear state space model.

$$\dot{x}_i = A_i x_i + B_i u_i \quad (10)$$

where

$$A_i = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21} & -\dfrac{D_i}{M_i} & a_{23} & a_{24} \\ a_{31} & 0 & a_{33} & -\dfrac{G_{ii}\Delta x_{di}}{T'_{d0i}} \\ a_{41} & 0 & \dfrac{G_{ii}\Delta x_{qi}}{T'_{q0i}} & a_{44} \end{bmatrix}, B_i = \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{T'_{d0i}} \\ 0 \end{bmatrix} \quad (11)$$

with elements that are given in [15].

3.2 Overall Control Framework

The overall control structure is shown in Fig. 1, where the conventional power system stabilizer and automatic voltage regulator blocks are replaced by a single H∞-SOF controller including the following optimal gain vector.

$$K_i^T = \begin{bmatrix} k_{vi} & k_{pi} & k_{\omega i} \end{bmatrix} \quad (12)$$

The H∞-SOF controller uses the terminal voltage Δv_{ti}, electrical power Δp_{ei} and machine speed $\Delta\omega_i$ as input signals, which all of them are easily measurable in a real power system environment. Δv_{refi} and d_i show the reference voltage deviation and system disturbance input, respectively.

Using linearized model for a given power system unit "i" in the form of (1) and performing the standard H∞-SOF configuration with considering an appropriate controlled output signals results an effective control framework, which is shown in Fig. 1. 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 optimal tuning of a pure vector gain. Here, disturbance input vector w_i, controlled output vector z_i and measured output vector y_i are considered as follows:

$$w_i^T = \begin{bmatrix} \Delta v_{refi} & d_i \end{bmatrix} \quad (13)$$

$$z_i^T = \begin{bmatrix} \mu_{1i}\Delta v_{ti} & \mu_{2i}\Delta\delta_i & \mu_{3i}\Delta P_{ei} & \mu_{4i}u_i \end{bmatrix} \quad (14)$$

$$y_i^T = \begin{bmatrix} \Delta v_{ti} & \Delta p_{ei} & \Delta\omega_i \end{bmatrix} \quad (15)$$

where $\mu_i = \begin{bmatrix} \mu_{1i} & \mu_{2i} & \mu_{3i} & \mu_{4i} \end{bmatrix}$ is a constant weight vector that must be chosen by designer to get the desired closed-loop performance. The selection of constant weights μ_{1i}, μ_{2i} and μ_{3i} is dependent on specified voltage regulation and damping performance goals. Actually, a significant issue for selecting of these weights is the degree to which they can guarantee the satisfaction of design performance goals. One can simply fix the weights to unity and use the method with regional pole placement technique for performance tuning [16].

The selection of these weights entails a compromise among several performance requirements. Furthermore, μ_{4i} sets a limit on the allowed control signal to penalize fast changes, large overshoot with a reasonable control gain to meet the feasibility and the corresponded physical constraints. Since the vector z_i properly covers all 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 satisfy the voltage regulation and stabilizing objectives, simultaneously.

As we know, considering the speed deviation as control input signal, the conventional PSS is structurally composed of phase-lead compensator(s), which acts like as a proportional-derivative (PD) controller. The proposed control system has the feedbacks from speed and electric power deviation signals, and, actually these two signals give the PD information of generator speed.

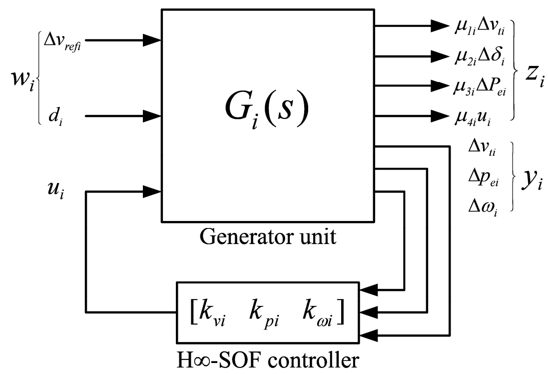

Fig. 1: The proposed H∞-SOF control framework

Furthermore, the additional feedback for the voltage deviation is similar to the used one in the conventional AVR (with a quite small time delay) for the measurement of voltage signal.

It is notable that, since the solution must be obtained trough the minimizing of an H∞ optimization problem, the designed controller satisfies the robust stability and voltage regulation performance for the closed-loop system. Moreover, the developed iterative LMI algorithm (which is described in the next section) provides an effective and flexible tool to find an appropriate solution in the form of a simple static gain controller.

3.3 An Iterative LMI Algorithm

In order to solve the H∞-SOF, an iterative LMI algorithm has been used. Similar to the given approach in Ref. [17, 18], the key point is to formulate the H∞ problem via a generalized static output stabilization feedback such that all eigenvalues of $(A\text{-}B\,K_i\,C)$ shift towards the left half plane in the complex s-plane, to close to feasibility of (3). The described theorem in the previous section gives a family of internally stabilizing SOF gains is defined as K_{sof}. But the desirable solution K_i is an admissible SOF law

$$u_i = K_i y_i \ , \ K_i \in K_{sof} \quad (16)$$

such that

$$\left\| T_{zi\,wi}(s) \right\|_\infty < \gamma^* , \ \left| \gamma - \gamma^* \right| < \varepsilon \quad (17)$$

where ε is a small positive number. Suboptimal performance index γ^* indicates a lower bound such that the closed-loop system is H∞ stabilizable. The optimal performance index (γ), can be obtained from the application of a full dynamic H∞ dynamic output feedback control method.

The proposed algorithm, which is described in Fig. 2, gives an iterative LMI suboptimal solution for above optimization problem. Here A_g, B_g and C_g are three generalized matrices of the following forms

$$A_g = \begin{bmatrix} A_i & B_{1i} & 0 \\ 0 & -\gamma I/2 & 0 \\ C_{1i} & 0 & -\gamma I/2 \end{bmatrix}, \ B_g = \begin{bmatrix} B_{2i} \\ 0 \\ D_{12i} \end{bmatrix}, \ C_g = \begin{bmatrix} C_{2i} & 0 & 0 \end{bmatrix} \quad (18)$$

The proposed iterative LMI algorithm shows that if we simply perturb A_g to $A_g - (a/2)I$ for some $a > 0$, then we will find a solution of the matrix inequality (3) for the performed generalized plant. That is, there exist a real number $(a > 0)$ and a matrix $P>0$ to satisfy inequality (II) given in Fig. 2. Consequently, the closed-loop system matrix $A_g - B_g K C_g$ has eigenvalues on the left-hand side of the line $\Re(s) = a$ in the complex s-plane. Based on the idea that all eigenvalues of $A_g - B_g K C_g$ are shifted progressively towards the left half plane through the reduction of a. The given generalized eigenvalue minimization in the developed iterative LMI algorithm guarantees this progressive reduction.

The selection method for the constant weight vector μ_i, includes the following steps:
Step 1. Set initial values,
Step 2. Run the iterative LMI algorithm shown in Fig. 2,
Step 3. If the ILMI algorithm gives a feasible solution such that satisfies the robust H∞ performance and the gain constraint; the assigned weights vector is acceptable. Otherwise retune μ_i and go to Step 2.

4. Real-Time Experiment

4.1 Real-Time Implementation

To illustrate the effectiveness of the proposed control strategy, a real time experiment has been performed on the large scale Analog Power System Simulator [19], at the Research Laboratory of the Kyushu Electric Power Company.

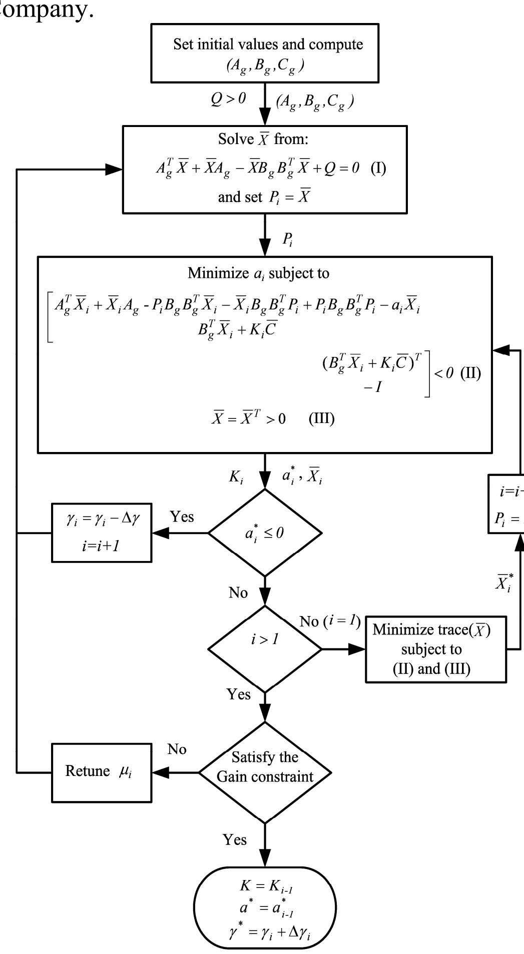

Fig. 2: Iterative LMI algorithm

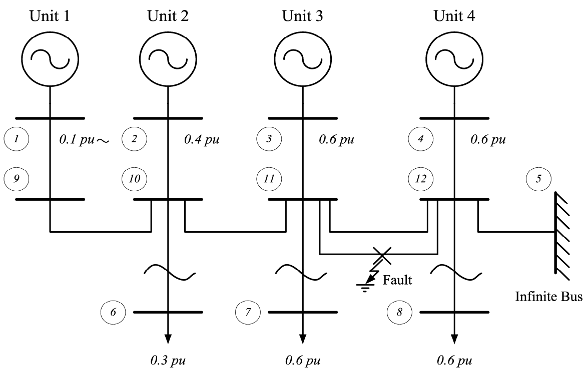

Fig. 3: Four-machine infinite-bus power system

For the purpose of this study, a longitudinal four-machine infinite bus system is considered as the test system. A single line representation of the study system is shown in Fig. 3.

Although, in the given model the number of generators is reduced to four, it closely represents the dynamic behavior of the west part of Japan (West Japan Power System), and it is widely used by Japanese researchers [20, 21]. The most important global and local oscillation modes of actual system are included. Units 2, 3 and 4 have a separately conventional excitation control system. The generators, lines and conventional excitation system parameters are given in [20, 21]. Unit 1 is equipped with robust control, and therefore our goal is to apply the control strategy developed in the previous section for designing of desirable controller for unit 1.

The whole power system has been implemented in the mentioned laboratory. Figs. 4a and 4b show the overview of the applied laboratory experiment devices including the control/monitoring desks. A digital oscilloscope and a notebook computer (shown in Fig. 4b) are used for monitoring purposes.

(b)

Fig. 4: Performed laboratory experiment; a) an overview, b) the control/monitoring desks.

The proposed control loop has been built in a personal computer (Fig. 4b) were connected to the power system using a digital signal processing (DSP) board equipped with analog to digital (A/D) and digital to analog (D/A) converters as the physical interfaces between the personal computer and the analog power system hardware.

First of all, using *hinflmi* function in LMI toolbox of MATLAB software [22], a full order robust dynamic controller with the following structure is designed.

$$K_1(s): \begin{array}{l} \dot{x}_K = A_K x_K + B_K y_1 \\ u_1 = C_K x_K + D_K y_1 \end{array} \quad (19)$$

Then, applying the proposed H∞-SOF control methodology an optimal gain vector for the problem at hand is obtained as follows.

$$K_{1,SOF} = [9.9897 \quad 8.9987 \quad 1.5986] \quad (20)$$

The value of 10 is considered as upper limit for the gains of vector's arrays. The used constant weight vector (μ_i) is obtained as $\mu_1 = [500 \quad 5 \quad 0.5 \quad 110]$. The considered constraints on limiters and control loop gains are set according to the real power system control units and close to ones that exist for the conventional AVR_PSS units. In the simulated example, since the conventional PSS gain and the AVR gain have been set to 10, to perform the fair comparisons between the conventional PSS-AVR and the proposed controller, both feedback gains k_{vi} and k_{pi} have been limited to 10 (as an upper bound constraint). Also, in comparison of conventional P+ω type PSS, the assigned gain for $k_{\omega i}$ is small enough.

In a real power system, the excitation voltage should be not rise from the accepted level after applying the shutdown test to the target generator. The gain setting for the proposed controller does not give any unacceptable excitation voltage rise during the shutdown test. When never applying the shutdown test, the PSS is usually locked among a quite short time after opening the generator circuit breaker. Therefore, even if the gains are little bit higher, then there still does not cause any problem for the excitation voltage increase.

The closed loop performance analysis shows that the resulted robust performance indices (γ and γ^*) of both synthesis methods are very close to each other (Table 1). It indicates that although the proposed H∞-SOF approach gives a much simpler controller (pure gain) than the H∞ dynamic output feedback design, it holds robust performance as well as dynamic H∞ controller.

4.2 Experimental Results

The performance of the closed-loop system in comparison of a full-order dynamic H∞ output feedback controller is tested in the presence of voltage deviation, faults and system disturbance. During the real-time nonlinear experiments, the output setting of unit 1 is fixed to 0.6 pu.

Fig. 5 shows the electrical power, terminal voltage and machine speed of unit 1, and the electrical powers of other units, following a fault on the line between buses 11 and 12 at 2 *sec*. The fault is continued for 4 cycles. As the next test case, the performance of designed controllers was evaluated in the presence of a 0.05 pu step disturbance injected at the voltage reference input of unit 1 at 20 *sec*. Fig. 6 shows the closed-loop response of the power systems fitted with the dynamical H∞ controller and the proposed robust gain vector.

Comparing the experiment results shows that the robust design achieves robustness against the voltage deviation, disturbance and line fault with a quite good performance as well as full dynamical H∞ controller. Furthermore, practically it is highly desirable, for reasons of simplicity of structure and flexibility of design methodology. Table 1 shows a comparison between the proposed H∞-SOF and H∞-Dynamic approaches in view point of structure, robust performance indices and the critical power output from unit 1 for a three-phase to ground fault (between buses 11 and 12 in Fig. 3).

The size of resulted stable region by both methods is approximately equal, and it is significantly enlarged in comparison of conventional AVR-PSS controller. Using the conventional AVR-PSS structure, the resulted critical power output from unit 1 to be 0.31 pu [20, 23]; and in case of tight tuning of parameters it will not to be higher than 0.5 pu.

Table 1: Comparison of H∞-based proposed robust control designs

Control design	*Control structure*	*Robust Perf. index*	*Critical power output*
H∞-Dynamic	High order	γ =*455.1052*	*0.95* (*pu*)
H∞-SOF	Pure gain	γ^* =*456.3110*	*0.93* (*pu*)
AVR-PSS	Conventional	-	*0.50* (*pu*)

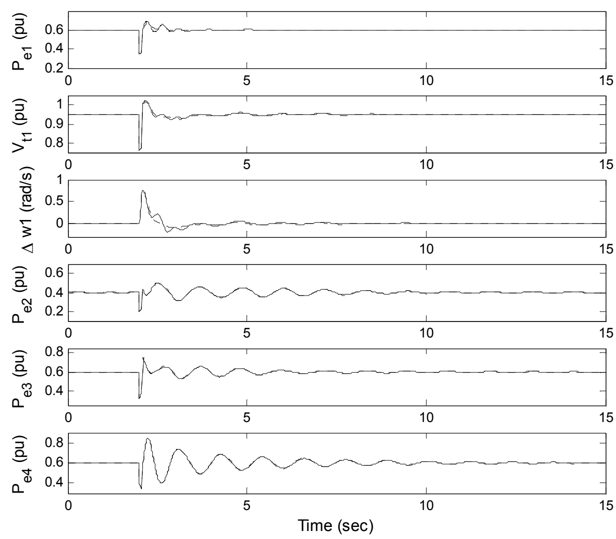

Fig. 5: System response for a fault between buses 11 and 12; Solid (H∞-SOF), dotted (H∞-Dynamic).

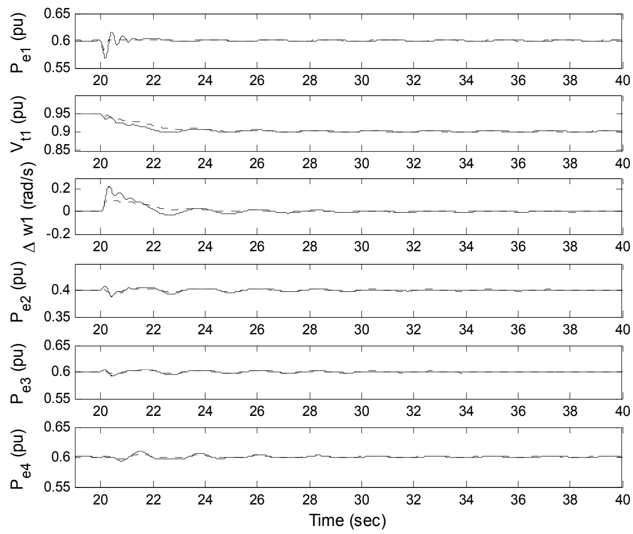

Fig. 6: System response for a 0.05 pu step change at the voltage reference input of unit 1; Solid (H∞-SOF), dotted (H∞-Dynamic).

5. Conclusion

In order to simultaneous enhancement of power system stability and voltage regulation, a new control strategy is developed using an H∞-SOF control technique via a developed iterative LMI algorithm. The proposed method was applied to a four-machine infinite bus power system, through a laboratory real-time experiment, and the results are compared with a full-order dynamical H∞ control design. The performance of the resulting closed-loop system is shown to be satisfactory over a wide range of operating conditions.

Making an effective and direct trade-off between voltage regulation and damping improvement, decentralized property, keeping the fundamental AVR-PSS concepts, ease of formulation for stability and performance requirements and flexibility of design methodology to give a feasible solution are the main advantages of the developed methodology.

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