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A New Robust Multi-Machine Power System Stabilizer Design Using Quantitative Feedback Theory

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Abstract

Small-signal oscillations is one of the important problems in power system operation that caused by insufficient natural damping in the system. This paper uses the Quantitative Feedback Theory (QFT) to design a new robust PSS for multi-machine power systems able to provide acceptable damping over a wide range of operating points. In the design procedure the main purpose is to reject the load fluctuations and, therefore, a particular transfer function is used as the nominal plant. The parametric uncertainty in power system is readily handled using QFT. The decentralized design with a simple structure is easily applied to multi-machine power systems. The nonlinear time-domain simulations are carried out to validate the effectiveness of the proposed controller. Results clearly show the benefits of the proposed controller for stability enhancement of power systems.

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Keywords: power system stabilizer, quantitative feedback theory, robust controller, multi-machine power system.

1. Introduction

Power system utilities use power system stabilizers (PSS) to enhance damping of low frequency oscillation. It is performed by providing supplementary stabilizing feedback signal in the excitation systems [1-3].

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The commonly used PSS is a fixed parameter device designed by using the classical linear theory and a linear model of the power system at a specific operating point. However, the inherent non-linearity and multiple operating points of a power system may degrade the performance of such a fixed gain PSS [4].

Application of the adaptive control theory can take into consideration the non-linear and stochastic characteristics of the power system [4-7]. Parameters of the adaptive stabilizers are adjusted on-line according to the operating condition. These methods, however, require either information on the system states or an efficient on-line identifier. Model reference adaptive techniques also require of satisfying the perfect model-following conditions and the complete system state information. Since the order of the power system is large, the model reference approach may be difficult to apply.

More recently artificial neural networks (ANN) and fuzzy set theoretic approaches have been proposed for power system stabilization problems [8-11]. Both techniques have their own advantages and disadvantages. Training of an ANN is a major exercise, because it depends on various factors [12] such as the availability of sufficient and accurate training data, suitable training algorithm, number of neurons in the ANN, number of ANN layers. The generalized neuron (GN) predictor is used to cope with this problem of complexity [13]. However, to be able to have a robust controller adaptive techniques are usually utilized with ANN and fuzzy techniques.

This paper presents a new robust explicit lead-lag controller in which QFT is applied to take care of the plant parameters variation. There have been a few previous reported applications of quantitative design methods in power systems. Jacobson et al. [14] have used QFT-like loop shaping to satisfy frequency response bounds derived using dissipative theory. Boje et al. [15] have applied QFT for PSS design in a single-machine-infinite-bus (SMIB) system. The method given in [15] uses only a part of QFT theory and the design procedure will be then different from what given in this paper. The QFT has been addressed in [16,17] for a multi-machine power system. The design procedure here is not only different, it has got a much simpler structure than the methodology given in [16] and it can be easily applied to a multi-machine power system. The method in [17] also uses a complicated multi-input-multi-output (MIMO) transfer function for decentralized design. However, in this paper a simple single-input-single-output (SISO) transfer function has been derived for one machine in a multi-machine power system with also considering the effect of other generators.

The proposed method is mainly based on the technique given in [18]. Simulation results imply that a desirable performance can be achieved when the proposed PSS is used in a multi-machine power system.

2. Modelling

The 3-order transfer function of one generator has been shown in Equation (1).

$$P(s,\xi)=\frac{\Delta\omega}{\Delta \mathrm{T}_m}=\frac{E_1(s,\xi)\cdot s^2+E_2(s,\xi)\cdot s}{s^3+F_1(s,\xi)\cdot s^2+F_2(s,\xi)\cdot s+F_3(s,\xi)} \tag{1}$$

Where, ζ refers to uncertainty of parameter. The parameters E_1, E_2, F_1, F_2, F_3 including "k" coefficients are given in Appendix.

2.1. Multi-machine Power System

Although the design of any supplementary controller on a one-machine system is logically the best place to begin an evaluation of the controller, a more thorough investigation has to be done with a multi-machine model. For a multi-machine case the linearized block diagram which is an extension of Figure 1 with also considering the effect of tie-line power is shown in Figure 2 [19-21].

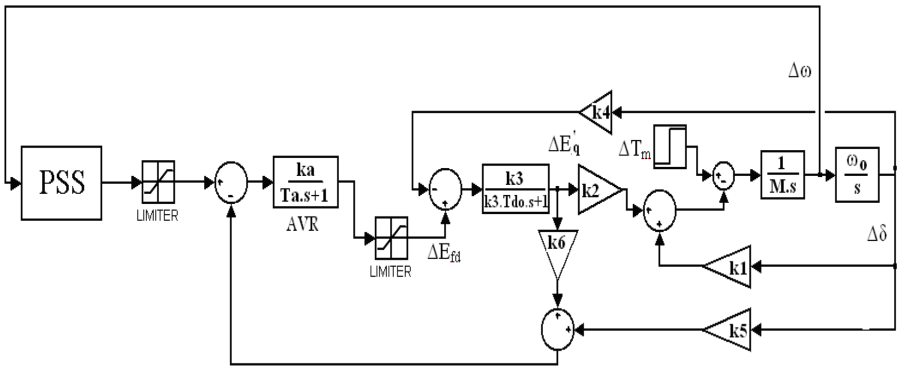

Fig. 1. Block diagram of the power system used for low frequency oscillation studies[19]

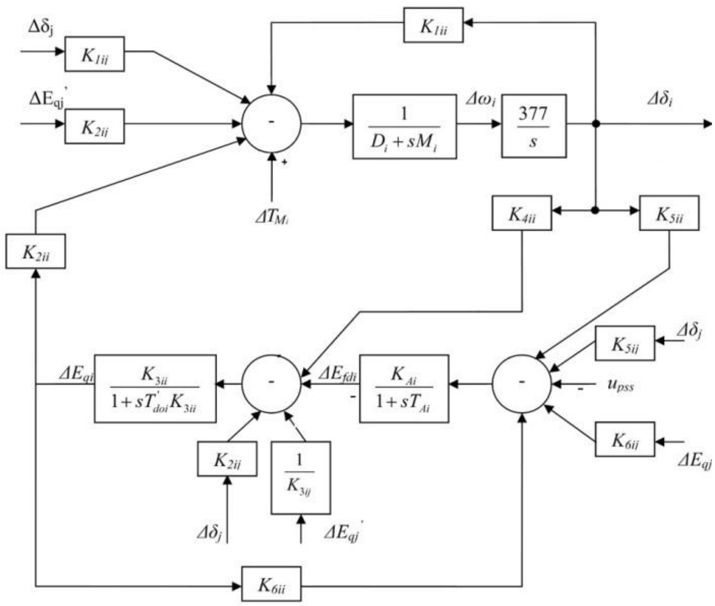

Fig. 2. Block diagram of ith machine in a multi-machine power system

Equation (1) will be also used here as the main transfer function of ith machine in a multi-machine system to design a decentralized power system stabilizer with also considering the effect of other generators in this machine. This will be explained in the next section.

3. State space representation

The state equation of an interconnected power system with n synchronous generators can be written in the vector-matrix differential equation form

$$\dot{x} = Ax(t) + Bu(t) + Fd(t) \tag{2}$$

where x(t) is the state vector (Δω, Δδ, $\Delta E'_q$), u(t) is the PSS output signals, d(t) is the input vector represented here by ΔTmi and A, B and F are constant matrices. For n-machine system the Equation (2) can be given as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ . \\ . \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & . & . & A_{1n} \\ A_{21} & A_{22} & . & . & A_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ A_{n1} & A_{n2} & . & . & A_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{bmatrix} + [B] \begin{bmatrix} u_1 \\ u_2 \\ . \\ . \\ u_n \end{bmatrix} + [F] \begin{bmatrix} d_1 \\ d_2 \\ . \\ . \\ d_n \end{bmatrix} \tag{3}$$

In Equation (3)A_{11}, A_{22}, … and A_{nn} are the local system matrices of the individual machines; and the off-diagonal matrices represent the paths of dynamic interactions between machines.

In this step of the design the control signals (u(t)) will be considered zero. This implies that the Equation (3) will be

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ . \\ . \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & . & . & A_{1n} \\ A_{21} & A_{22} & . & . & A_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ A_{n1} & A_{n2} & . & . & A_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{bmatrix} + [F] \begin{bmatrix} d_1 \\ d_2 \\ . \\ . \\ d_n \end{bmatrix} \tag{4}$$

The following three methods may be then considered to design the PSS parameters using QFT for each machine.

1- The power system stabilizers are designed for each generator simultaneously for the entire system.

2- Completely ignoring the dynamic interaction between machines, controllers are designed separately from local system dynamics (see Equation (5)).

$$\dot{x}_1 = A_{11}x_1 + F_1 d_1,\ \dot{x}_2 = A_{22}x_2 + F_1 d_1, \ldots, \\ \dot{x}_n = A_{nn}x_n + F_n d_n \tag{5}$$

3- Both x_1 ,…, x_{n-1} and d_1,…,d_{n-1} are omitted from Equation (4) and a decentralized design is applied for $\dot{x}_n$ with also considering the effect of other state variations (x_1,…,x_{n-1}) of the entire system as shown in Equation (6).

$$\begin{bmatrix} 0 \\ 0 \\ . \\ . \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & . & . & A_{1n} \\ A_{21} & A_{22} & . & . & A_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ A_{n1} & A_{n2} & . & . & A_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{bmatrix} + [F] \begin{bmatrix} 0 \\ 0 \\ . \\ . \\ \Delta T_{mn} \end{bmatrix} \tag{6}$$

The first method gives best result but makes the design procedure be complicated and time consuming. The second one does not work in harmony, leading only to system instability, which is rather as excepted [19]. Therefore, the best choice is the third method because it has much simpler structure for control design and is almost as equally effective as the first one [19].

Now the following algorithm is given to obtain the nominal plant of the nth machine $P_n(s) = (\Delta\omega_n/\Delta Tm_n)$. After considering Equation (6), Equations (7) and (8) can be derived as follows:

$$\begin{aligned} &A_{11}x_1 + A_{12}x_2 + \ldots + A_{1n}x_n = 0, \\ &A_{21}x_1 + A_{22}x_2 + \ldots + A_{2n}x_n = 0, \ldots \\ &A_{(n-1)1}x_1 + A_{(n-1)2}x_2 + \ldots + A_{(n-1)n}x_n = 0 \\ &\dot{x}_n = A_{n1}x_1 + A_{n2}x_2 + \ldots + A_{nn}x_n + F_n \Delta T_{mn} \end{aligned} \tag{7}$$

And

$$\begin{aligned} &-[A_{1n}]^{-1}[A_{11}x_1 + A_{12}x_2 + \ldots + A_{1(n-1)}x_{n-1}] = x_n, \ldots \\ &-[A_{(n-1)n}]^{-1}[A_{(n-1)1}x_1 + A_{(n-1)2}x_2 + \ldots + A_{(n-1)(n-1)}x_{n-1}] = x_n \end{aligned} \tag{8}$$

From Equation (8) the state variations of $x_1, \ldots, x_{n-1}$ are obtained as multiple of x_n and shown in Equation (9).

$$x_1 = A_1' x_n, x_2 = A_2' x_n, \ldots, x_{n-1} = A_{n-1}' x_n \tag{9}$$

Matrices $A'_1, \ldots, A'_{n-1}$ can be easily obtained by solving Equation (8). Combining Equations (7), (8) and (9) leads to have

$$\begin{aligned} &\dot{x}_n = A_{n1}x_1 + A_{n2}x_2 + \ldots + A_{nn}x_n + F_n d_n \\ &\dot{x}_n = [A_{n1}A_1' + A_{n2}A_2' + \ldots + A_{n(n-1)}A_{n-1}' + A_{nn}]x_n + F_n \Delta T_{mn} \end{aligned} \tag{10}$$

4. QFT-based design

4.1. Fundamental

Quantitative Feedback Theory is a robust control method developed during the last two decades by Horowitz and others [22, 23]. It deals with the effects of uncertainty systematically. It has been successfully applied to the design of both SISO and MIMO systems. It has been also extended to the nonlinear and the time-varying cases.

In comparison with other optimization-based robust control methods, QFT offers a number of advantages. These include: (1) the ability to assess quantitatively the 'cost of feedback' [22], (2) the ability to take into account phase information in the design process, and (3) the ability to provide 'design transparency', that is, clear tradeoff criteria between controller complexity and feasibility of the design objectives. The third advantage in practice implies that QFT leads to have a simple controller which is very easy to implement.

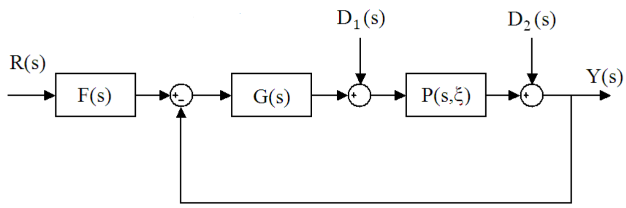

Fig. 3. Block diagram of the system with the controller in QFT design

For the purposes of QFT, the feedback system is normally described by two degrees-of-freedom structure shown in Fig. 3.

In QFT the closed loop transfer function should satisfy certain performance requirements for a set of discrete frequencies. These requirements are specified in terms of tolerance bounds within which the magnitude response of the closed-loop transfer function should be limited. The uncertainties in the plant are transformed onto the Nichols chart resulting in bounds on the open loop transfer function of the system (P(s)). A compensator (G(s)) is then chosen by manually shaping the loop transmission so that it satisfies the bounds at each of the frequency points. A pre-filter (F(s)) is then used to ensure that the closed-loop transfer function lies within the specified bounds.

In Figure 3 P(s, ζ) represent the nominal power system plant given in section II. $D_2(s)$ will be equal to zero and $D_1(s)$ represents the torque changes, ΔT_m. As mentioned before the purpose of this design procedure is to reject load fluctuations and, therefore, R(s) representing ΔV_{ref} (see Figure 1) will be zero [25]. After designing the controller G(s) using QFT, it will be put in the feedback path as shown in Figure 4. In fact, its output stabilizing signal will be inserted into the summing junction where the AVR system is connected. The transfer function $P_1(s) = (\Delta\omega/\Delta V_{ref})$ shown in Figure 4 is different from P(s) but has the same denominator of P(s). It should be noted that since a washout [19] will be used in cascade with G(s), it does not affect on the steady state performance of the system. The controller G(s) will be then the new designed PSS. Block diagram of PSS is given in Figure 5.

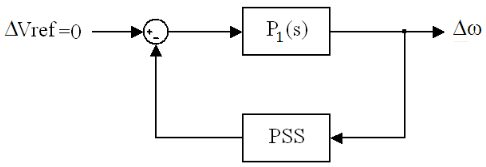

Fig. 4. Block diagram of the system with the designed controller

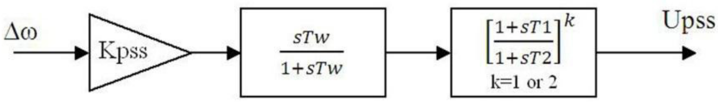

Fig. 5. Block diagram of the PSS

4.2. QFT-based design

In QFT design there are two primary control objectives. The first is stability with reasonable margins of

$$\left|\frac{PG(j\omega)}{1+PG(j\omega)}\right| \leq 1.2, \omega > 0$$

and the second is disturbance rejection and is considered here as

$$\left|\frac{\Delta\omega(j\omega)}{\Delta T_m(j\omega)}\right| \leq 0.01$$

A continuous-time uncertain transfer function model can have parametric, non-parametric or mixed parametric and non-parametric structures. Parametric uncertainty which is the case in this study implies the knowledge of variations in "K" parameters (e.g., see Appendix for SMIB and multi-machine systems).

One of the most important factors in control design is to use an accurate description for the plant dynamics. Because QFT involves frequency-domain arithmetic, its design procedure requires us to define plant dynamics only in terms of its frequency response. The term template is then used to denote the collection of an uncertain plant's frequency responses at a given frequency. The frequency range must be chosen based on the performance bandwidth and shape of the templates. Margin bounds should be computed up to the frequency where the shape of the plant template becomes invariant to frequency. The plant templates at several frequencies for a SMIB system example given in Appendix are shown.

4.3. Multi-machine power system

A three-machine power system taken from [24] is shown in Figure 6 and the system data is given in Appendix.

The electromechanical modes of the system are shown in Table I. The system is unstable and the need for stabilizers to damp out rotor oscillations is evident.

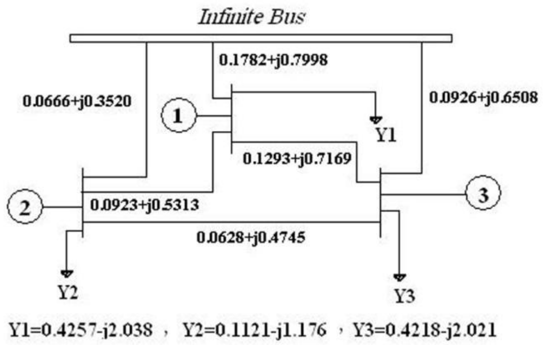

Fig. 6. Single line diagram of three-machine power system

A stabilizer is first designed for machine #3 in which the electromechanical mode 0.275±j4.08 oscillates. The state equation of this system is given by

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + [F] \begin{bmatrix} \Delta T_{m1} \\ \Delta T_{m2} \\ \Delta T_{m3} \end{bmatrix} \tag{11}$$

Assuming that $\dot{x}_1 = \dot{x}_2 = 0$ and ΔTm1= ΔTm2=0 implies that

$$\begin{bmatrix} 0 \\ 0 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + [F] \begin{bmatrix} 0 \\ 0 \\ \Delta T_{m3} \end{bmatrix} \tag{12}$$

Then by using the procedure given in Section III the Equation (13) is obtained as follows;

$$\left[\dot{x}_3 \right] = \left[A_{31}A_1A_2 + A_{32}A_2 + A_{33} \right] [x_3] + \begin{bmatrix} 0 \\ \dfrac{1}{m_3} \\ 0 \end{bmatrix} \Delta T_{m3} \tag{13}$$

Where

$$A_1 = (A_{13}^{-1} A_{11} - A_{23}^{-1} A_{21})^{-1} (A_{23}^{-1} A_{22} - A_{13}^{-1} A_{12})$$

$$A_2 = -(A_{11} A_1 + A_{12})^{-1} A_{13}$$

The transfer function $P_3(s) = (\Delta\omega_3/\Delta Tm_3)$ can be then obtained from Equation (13). This has been shown for power system example given in Figure 6 as follows;

$$p_3(s) = \frac{\Delta\omega_3}{\Delta T_{m3}} = \frac{26.17 \cdot s^2 + 18.19 \cdot s}{s^3 + 0.52 \cdot s^2 + 22.7 \cdot s + 15.76}$$

The range of frequency [4-8 rad/s] is chosen for QFT design (see Table I). Figures 7 shows the robust input disturbance rejection bound for generator 3 respectively. Intersection of all bounds (robust stability & disturbance rejection bounds) is shown in Figure 8.

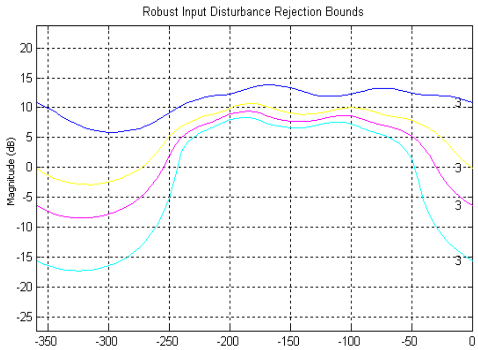

Fig. 7. Disturbance rejection bounds of machine 3

Table1: Electromechanical Modes of Three-Machine Power System Without PSS

Electromechanical Modes
-0.065+j7.39
0.099±j7.82
0.275±j4.08

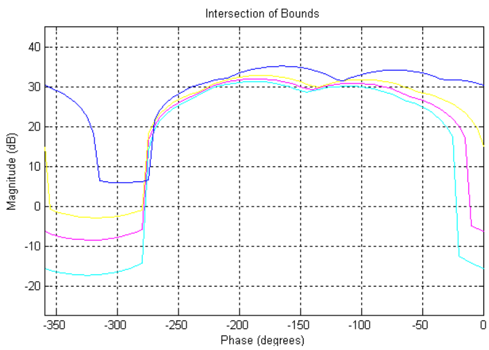

Fig. 8. Intersection of all bounds in machine 3

The last stage of controller design is loop shaping of open loop transfer function in machine 3 and shown in Figure 9.

Finally the controller is obtained from QFT method as follows;

$$G_3(s) = 75.\frac{0.65s+1}{0.1s+1}.\frac{0.65s+1}{0.1s+1}$$

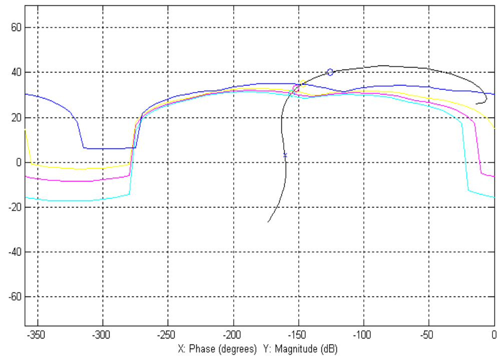

Fig. 9. Loop shaping for machine 3

For machine 1 and machine 2 the design procedure is performed accordingly and $G_1(s)$ and $G_2(s)$ are given in appendix.

5. Simulation Result

The nonlinear simulations are also carried out for the system given in section IV.C. The speed rotor variation of machines 1 following a small change (1%) in the load of machine 1 are shown in Figure 10.

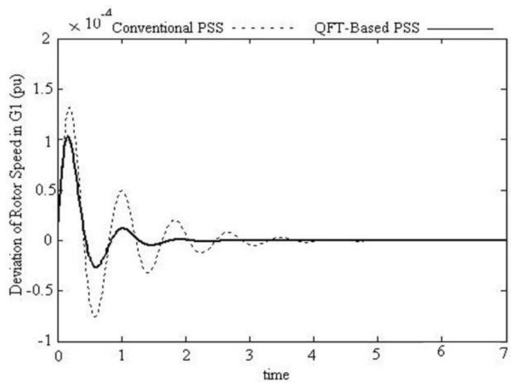

Fig. 10. Speed rotor variation of G1 following a small change in load G1 (1%)

The speed rotor variations of machine1 is shown in Figure 11 when a small change in load (1%) in machine 1 at initial time, in generator 2 at second 10 and in generator 3 at second 20 occurs. In this test all parameters of the system also change by 20%. As can be seen the QFT-based PSS depicts more desirable performance than the conventional one.

Table 2 also shows eigen values of the system. As can be seen from this table electromechanical modes of the system are better damped when QFT-based PSS is used.

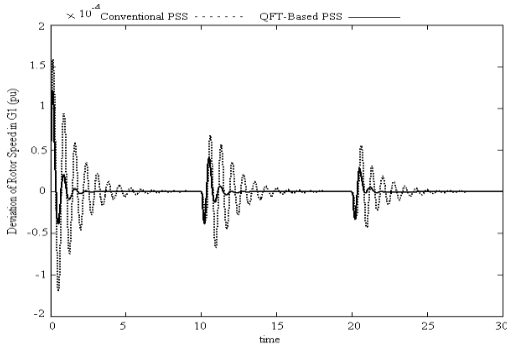

Fig. 11. Speed rotor variation of G1 following small change in load of machines when all of parameters in system change (20%)

Table 2: Eigen values of Three-Machine Power System

Without PSS	With QFT-Based PSS	With Conventional PSS
-0.065±j7.39	-3.83±j7.23	-3.13±j6.54
0.099±j7.82	-5.26±j5.65	-4±j6.8
0.275±j4.08	-1.8±j4.66	-1.58±j2.98
-1.52	-1.38	-1.47
-3.43	-5.2	-3.42
-5.92	19.13	-8.9
-15.18	-10.2	-31.99
-17.05	-2.1±j3.9	-6.21±j7.09
-18.87	-4.48±j9.55	-6.59±j13.82
	-7.45±j8.41	-8.86±j16.34
	-10.45±j6.12	-37.27±j1.22

6. conclusion

In this paper, a quantitative design approach for tuning stabilizers in multi-machine power systems has been presented. A new decentralized technique is used to design a robust PSS for each generator. QFT-based PSS like the conventional lead-lag compensator can be easily implemented for real-time applications. Simulation results confirm the robustness and desirable performance of the proposed PSS when compared with the conventional one, especially where the parameters of the system change.

Appendix

1-Parameters of P(s) in 3-order Transfer Function

$$E1(s)=\frac{1}{\omega_0\cdot M} \quad , \quad E2(s)=\frac{(1+k_a\cdot k_3\cdot k_6)}{\omega_0\cdot k_3\cdot T_{do}\cdot M}$$

$$F1(s)=\frac{(1+k_a\cdot k_3\cdot k_6)\cdot M+D\cdot k_3\cdot T_{do}}{k_3\cdot T_{do}\cdot M} \quad , \quad M=\frac{m}{\omega_0}$$

$$F2(s)=\frac{(1+k_a\cdot k_3\cdot k_6)\cdot D+k_1\cdot k_3\cdot T_{do}}{k_3\cdot T_{do}\cdot M}$$

$$F3(s) = \frac{(1 + k_a \cdot k_3 \cdot k_6) \cdot k_1 - (k_2 \cdot k_3 \cdot (k_4 + k_a \cdot k_5))}{k_3 \cdot T_{do} \cdot M}$$

$$G_1(s) = 68.\frac{0.6s+1}{0.1s+1}.\frac{0.6s+1}{0.1s+1}, \quad G_2(s) = 71.\frac{0.63s+1}{0.1s+1}.\frac{0.63s+1}{0.1s+1}$$

2-Data of 3-machine power system

G1 : Xd=1.68 , Xq=1.66 , X'd=0.32 , Tdo=4 , H=2.31 , KA=40 , TA=0.05 , P=26 MW , Q=37 MVAR

Base Quantities: 360 MVA, 13.8 KV

G2 :Xd=0.88 , Xq=0.53 , X'd=0.33 , Tdo=8 , H=3.4 , KA=45 , TA=0.05 , P=518 MW , Q=-31.5 MVAR

Base Quantities: 503 MVA, 13.8 KV

G3 : Xd=1.02 , Xq=0.57 , X'd=0.2 , Tdo=7.76 , H=4.63 , KA=50 ,TA=0.05, P=1582 MW , Q=-69.9MVAR

Base Quantities: 1673 MVA, 13.8 KV

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