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Robust PID power system stabilizer design based on pole placement and nonlinear programming methods

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Abstract

Power system stabilizers (PSS) are used to generate supplementary damping control signals for the excitation system in order to damp the low frequency oscillations (LFO) of the electric power system. The PSS is usually designed based on classical control approaches but this conventional PSS (CPSS) has some problems. To overcome the drawbacks of CPSS, numerous techniques have been proposed in literatures. In this paper a new robust hybrid method based on the combination of pole placement and nonlinear programming methods is proposed in order to design a robust power system stabilizer. The classical robust methods usually lead to a high order controller which is expensive, difficult to implement and somehow impossible. As a solution, in this paper a PID type PSS is considered for damping electric power system oscillations. The parameters of this PID type PSS (PID-PSS) are tuned based on pole placement and nonlinear programming methods. Therefore, not only the obtained PID-PSS is low order and easy to implement but also it has robust characteristics like robust controllers. The proposed PID-PSS is evaluated against the conventional and robust power system stabilizers in a single machine infinite bus power system considering system parametric uncertainties. The simulation results clearly indicate the effectiveness and validity of the proposed method.

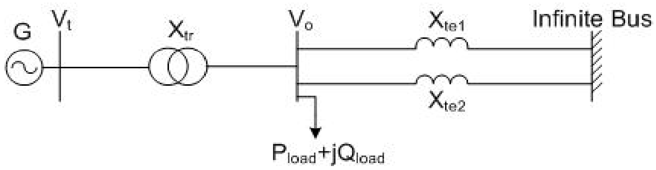
Keywords: Electric power system stabilizer, pole placement, nonlinear programming, robust control, PID controller.

Nomenclature: PSS: Power system stabilizer; CPSS: Conventional power system stabilizer; SISO: Single input - single output; MIMO: Multi input-multi output; PID: Proportional-integral-differential; ITAE: Integral of the time multiplied absolute value of the error; ω: Synchronous speed; δ: Synchronous angle; P_m: Input mechanical power; P_e: Output electrical power; M: Inertia; E_q: q axis voltage; E_{fd}: Field voltage; E'_q: Transient voltage of q axis; T'_{do}: Transient time constant of q axis; K_a: Excitation system gain; T_a: Excitation system time constant; V_t: Terminals voltage; V_{ref}: Reference voltage of excitation system; T_m: Mechanical torque; M_r: Maximum peak resonance of the closed loop system; M_p: Maximum peak overshoot.

Introduction

Large electric power systems are complex nonlinear systems and often exhibit low frequency electromechanical oscillations due to insufficient damping caused by adverse operating. These oscillations with small magnitude and low frequency often persist for long periods of time and in some cases they even present limitations on power transfer capability (Liu *et al.,* 2005). In analyzing and controlling the power system's stability, 2 distinct types of system oscillations are recognized. One is associated with generators at a generating station swinging with respect to the rest of the power system. Such oscillations are referred to as "intra-area mode" oscillations. The second type is associated with swinging of many machines in an area of the system against machines in other areas. This is referred to as "inter-area mode" oscillations. Power system stabilizers (PSS) are used to generate supplementary control signals for the excitation system in order to damp both types of oscillations (Liu *et al.,* 2005). The widely used conventional power system stabilizers (CPSS) are designed using the theory of phase compensation in the frequency domain and are introduced as a lead-lag compensator. The parameters of CPSS are determined based on the linearized model of the power system. Providing good damping over a wide operating range, the CPSS parameters should be fine tuned in response to both types of oscillations. Since power systems are highly nonlinear systems, with configurations and parameters which alter through time, the CPSS design based on the linearized model of the power system cannot guarantee its performance in a practical operating environment. Therefore, an adaptive PSS which considers the nonlinear nature of the plant and adapts to the changes in the environment is required for the power system (Liu *et al.,* 2005). In order to improve the performance of CPSSs, numerous techniques have been proposed for designing them, such as intelligent optimization methods (Sumathi *et al.,* 2007; Jiang *et al.,* 2008; Sudha *et al.,* 2009; Linda & Nair, 2010; Yassami *et al.,* 2010) and Fuzzy logic method (Dubey, 2007; Hwanga *et al.,* 2008). Also many other different techniques have been reported by Chatterjee *et al.* (2009) and Nambu and Ohsawa (1996) and the application of robust control methods for designing PSS has been presented by Gupta *et al.* (2005), Mocwane and Folly (2007), Sil *et al.* (2009) and Bouhamida *et al.* (2005). This paper deals with a design method for the stability enhancement of a single machine infinite bus power system using PID-PSS which its parameters are tuned by pole placement and nonlinear programming methods. The combination of these two methods leads to a new robust PID-PSS with robust performance and PID configuration. The pole placement and nonlinear programming methods have been successfully applied to design SISO and MIMO systems and they have also been extended to the nonlinear and time-varying cases (Chow, 1988; Marsden *et al.,* 2004; Bazaraa *et al.,* 2006). To show effectiveness of the new nonlinear robust control method, this method is compared with the CPSS and robust PSS based on quantitative feedback theory (QFT). Simulation results show that the proposed method guarantees robust performance under a wide range of operating conditions. Apart from this introductory section, this paper is structured as follows. The system under study is presented in section 2. Section 3 describes about the system modeling and system analysis is presented in section 4. The power system stabilizers are briefly explained in section 5. Section 6 is devoted to explaining the proposed methods. The design methodology is developed in section 7 and eventually the simulation results are presented in section

Fig. 1. A single machine infinite bus power system.



System under study

Fig. 1 shows a single machine infinite bus power system (Kundur, 1993). The nominal loading condition and system parameters are given in the appendix and the static excitation system has been considered as model type *IEEE - ST1A*.

Dynamic model of the system

Non-linear dynamic model

A non-linear dynamic model of the system is derived by disregarding the resistances of all components of the system (generator, transformers and transmission lines) and the transients of the transmission lines and transformers (Kundur, 1993). The nonlinear dynamic model of the system is given as (1).

$$\begin{cases} \dot{\omega} = \dfrac{\left(P_m - P_e - D\Delta\omega\right)}{M} \\ \dot{\delta} = \omega_0\left(\omega - 1\right) \\ \dot{E}'_q = \dfrac{\left(-E_q + E_{fd}\right)}{T'_{do}} \\ \dot{E}_{fd} = \dfrac{-E_{fd} + K_a\left(V_{ref} - V_t\right)}{T_a} \end{cases} \quad (1)$$

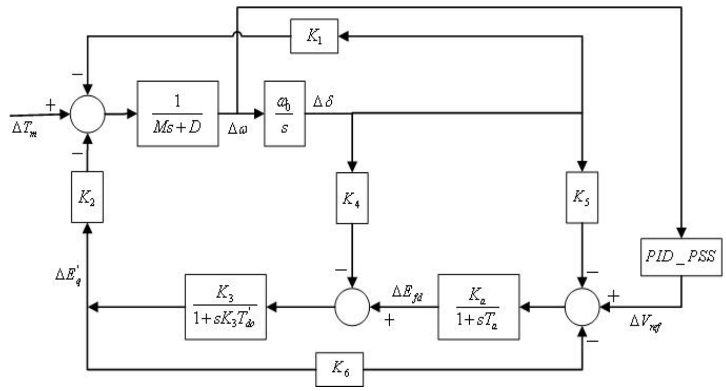
Linear dynamic model of the system

A linear dynamic model of the system is obtained by linearizing the non-linear dynamic model around the nominal operating condition. The linearized model of the system is obtained as (2) (Kundur, 1993).

$$\begin{cases} \Delta\dot{\delta} = \omega_0 \Delta\omega \\ \Delta\dot{\omega} = \dfrac{-\Delta P_e - D\Delta\omega}{M} \\ \Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\ \Delta\dot{E}_{fd} = -\left(1/T_A\right)\Delta E_{fd} - \left(K_A/T_A\right)\Delta V \end{cases} \quad (2)$$

Fig. 2 shows the block diagram model of the system. This model is known as Heffron-Phillips model (Kundur,

Fig. 2. Heffron-Phillips model of the power system.



1993). The model has some constants denoted by K_i. These constants are functions of the system parameters and the nominal operating condition.

Dynamic model of the system in the state-space form

The dynamic model of the system in the state-space form is obtained as (3) (Kundur, 1993).

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\dfrac{K_1}{M} & 0 & -\dfrac{K_2}{M} & 0 \\ -\dfrac{K_4}{T'_{do}} & 0 & -\dfrac{K_3}{T'_{do}} & \dfrac{1}{T'_{do}} \\ -\dfrac{K_A K_5}{T_A} & 0 & -\dfrac{K_A K_6}{T_A} & -\dfrac{1}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \dfrac{1}{M} & 0 \\ 0 & 0 \\ 0 & \dfrac{K_A}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta T_m \\ \Delta V_{ref} \end{bmatrix} \quad (3)$$

Table 1. The eigen values of the closed loop system.

-4.2797
-46.366
+0.1009 + j4.758
+0.1009 - j4.758

Eigen value analysis

In the nominal operating condition, the eigen values of the system are obtained using analysis of the state-space model of the system presented in (3) and these eigen values are shown in Table 1. It is clearly seen that the system has two unstable poles at the right half plane and therefore the system is unstable and needs the power system stabilizer (PSS) for stability.

Power system stabilizer

A power system stabilizer (PSS) is provided to improve the damping of power system oscillations. Power system stabilizer provides an electrical damping torque (ΔT_m) in phase with the speed deviation ($\Delta\omega$) in order to improve damping of power system oscillations (Kundur, 1993). As referred before, many different methods have been applied to design power system stabilizers so far. In this paper a new robust nonlinear hybrid method based on the combination of pole placement and nonlinear programming techniques is considered to design the power system stabilizer with PID configuration (PID-PSS). In the next section, the proposed methods are briefly introduced and then designing the PID-PSS, based on the proposed methods, is done.

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The proposed method

In this paper a combination of pole placement and nonlinear programming techniques is considered to design PID-PSS. For more introductions, the proposed methods are briefly introduced in the following subsections.

Nonlinear programming

Nonlinear programming deals with the problem of optimizing an objective function in the presence of equality and inequality constraints. If all the functions are linear, the problem is called a linear programming, otherwise; it is called a nonlinear programming. Considering the nature of nonlinearity of the objective function and nonlinearity of any of the constraints, many realistic problems cannot be adequately represented or approximated as a linear program. Efforts to solve such nonlinear programs efficiently have made rapid progress during the past four decades (Bazaraa *et al.,* 2006; Marsden *et al.,* 2004). Since the nonlinear programming method is the best method among other optimization methods and also the objective function and constraints, in this paper, are nonlinear functions, therefore the nonlinear programming method will be proposed to tune the PID-PSS parameters.

Pole placement

In this paper, the nonlinear programming is used with the combination of pole placement method. Pole placement is a classical method to design controllers and is introduced by Chow (1988). In pole placement the aim is to place the poles of the closed loop transfer function in reasonable positions. In fact it is possible to shape the closed loop system response by closed loop poles placement. The simple design principle is by placing the closed loop poles as desired, making the closed loop system (under control) faster and more stable when following command signal. The algorithm is based on polynomials manipulation. In the next section PID-PSS design methodology based on the pole placement and nonlinear programming methods is developed.

Design methodology

In this section PID-PSS design based on the nonlinear programming and pole placement methods are presented. At first the objective function should be introduced. The considered objective function is presented in the next subsection.

Objective function

In this paper an optimization method based on the nonlinear programming is considered to design PID-PSS. The tuning method of the PID-PSS is based on the contours of the Nichols chart, and the specification is given in terms of the maximum peak resonance M_r of the closed loop system. The PID-PSS parameter are adjusted so that the open loop transfer function $G(j\omega)$ follows the contour corresponding to the desired M_r. Therefore, the objective function is the distance between the open loop transfer function $G(j\omega)$ and the maximum peak response contour M_r of the closed loop system over a frequency region in the Nichols chart (Poulin & Pomerleau, 1997). The distance between $G(j\omega)$ and M_r is usually calculated in the Nyquist plane for mathematical convenience. This objective function has been successfully used to adjust PID controller parameters (Poulin *et al.,* 1997). Let h be a particular contour and $X(\omega)$ and $Y(\omega)$ be the real part and imaginary part of $G(\omega)$. The equation of the contour is as (4) (Poulin & Pomerleau, 1997).

$$h = \frac{|G(j\omega)|}{|1+G(j\omega)|} = \frac{|X(\omega)+jY(\omega)|}{|1+X(\omega)+jY(\omega)|} = \frac{\sqrt{X^2(\omega)+Y^2(\omega)}}{\sqrt{(1+X(\omega))^2+Y^2(\omega)}} \quad (4)$$

When $h=1$, the equation of the contour in the Nyquist plane is a straight line parallel to the imaginary axis as shown in (5) (Poulin & Pomerleau, 1997).

$$X(\omega) = -\frac{1}{2} \quad (5)$$

And the distance at a particular frequency ω_i, between $G(j\omega)$ and the contour is given by (6).

$$d_i = \left|X(\omega_i) + \frac{1}{2}\right| \qquad h = 1 \quad (6)$$

When $h > 1$, the contours are circular as shown in (7).

$$\left(X(\omega) - \frac{h^2}{1-h^2}\right)^2 + Y^2(\omega) = \left(\frac{h}{1-h^2}\right)^2 \quad (7)$$

and the distance at a particular frequency is ω_i as (8)

$$d_i = \sqrt{\left(X(\omega_i) - \frac{h^2}{1-h^2}\right)^2 + Y^2(\omega_i)} + \frac{h}{1-h^2} \qquad h > 1 \quad (8)$$

Finding controller parameters so that the distance between $G(j\omega)$ and M_r is a minimum over a frequency range is formulated as a constrained optimization problem in a frequency domain. Using (6) and (8), the objective function is given by (9) (Poulin & Pomerleau, 1997).

$$J(\theta_c) = \begin{cases} \sum_{i=1}^{k} \left|X(\omega_i) + \frac{1}{2}\right| & M_r = 0dB \\ \sum_{i=1}^{k} \left[\sqrt{\left(X(\omega_i) - \frac{h^2}{1-h^2}\right)^2 + Y^2(\omega_i)} + \frac{h}{1-h^2}\right] & M_r > 0dB \end{cases} \quad (9)$$

Where $_c$=[K_P, K_I, K_D] represents the PID controller parameters. In this paper in order to access the desired control characteristics of the power system, the parameter M_r is considered equal to 2 and so the second term of the $J(\ _c)$ is chosen as the objective function. In the next subsection the system constraints are presented.

Constraints

In the optimization process of the objective function, some performance limitations of the power system such as stability and response specifications should be regarded. These limitations are exerted as some constraints over the objective function to preserve some properties of the system. These constrains are as (10).

$$\begin{cases} 20\log|H(j\omega_r)| = M_r \\ |H(j\omega_r)| \geq 1 & \omega \leq \omega r \\ \angle G(j\omega co) > -180 \end{cases} \quad (10)$$

Where ω_r is the closed loop resonance frequency the ω_{co} is the open loop crossover frequency. The first constraint ensures that the specification is met and not

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exceeded. The second constraint ensures that the relationship between M_r and M_p (maximum peak overshoot) is preserved and the last constraint ensures that the system is stable. In the next subsection the PID-PSS parameters adjustment, using the proposed method, is presented.

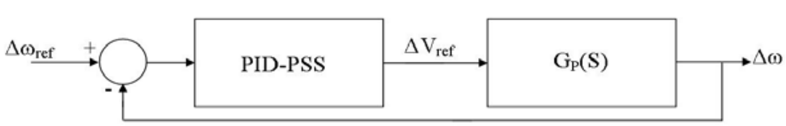
PID-PSS parameters tuning

As explained in the last sections, the PID-PSS parameters tuning leads to a nonlinear objective function with three nonlinear constraints that they make a nonlinear problem. Since one of the best methods to solve the nonlinear problems is the nonlinear programming, it is proposed here. Therefore the nonlinear problem with constraints can be rearranged as (11).

$$\begin{cases} J(\theta_c)=\sum_{i=1}^{k}\left[\sqrt{\left(X(\omega_i)-\frac{h^2}{1-h^2}\right)^2+Y^2(\omega_i)}+\frac{h}{1-h^2}\right] \qquad M_r>0dB \\ 20\log\left|H(j\omega_r)\right| = M_r \\ \angle G(j\omega_{cu})>-180^{\circ} \\ \left|H(j\omega_r)\right|\geq 1 \quad \omega\leq\omega r \end{cases} \qquad (11)$$

Where, the parameters $X(\omega)$ and $Y(\omega)$ are the real and imaginary parts of the open loop transfer function $G(j\omega)$, respectively. It should be note that $G(j\omega)$ is multiplication of the plant transfer function and a cascade controller as shown in Fig. 3. Where, $\Delta\omega_{ref}$ is considered zero, $G_P(s)$ is the plant transfer function and the PID-PSS configuration is as (12).

Fig. 3. The structure of closed loop system with controller.



$$PID\text{-}PSS = K_P + \frac{K_I}{s} + K_D S \quad (12)$$

First, the transfer function $G_P(s)$ is obtained using state-space model of the system presented in (3) and then the PID-PSS is applied to control the $G_P(s)$. Since the objective function and constraints are functions of the controller parameters (K_P, K_I, K_D), consequently the outputs of the nonlinear programming are the optimized controller parameters (K_P, K_I, K_D). This optimization algorithm is shown in the Fig. 4. The PID-PSS parameters have been obtained based on the above algorithm and listed in Table 2. It should be note that, the system without PSS is unstable (because of two unstable poles on the right half plane) and the PID-PSS stables the system with sliding the unstable poles on the right half plane to left half plane. This performance of PID-PSS is done by the defined constraints over the objective function. In other words when the nonlinear programming method optimizes the constrained objective function, the optimization algorithm performs so that the unstable poles are transferred to the left half plane. As mentioned before, this replacement of poles in order to achieve stability is known as pole placement. Therefore the nonlinear programming method has been combined with pole placement during the optimization procedure.

Fig. 4. The procedure of tuning PID-PSS using nonlinear

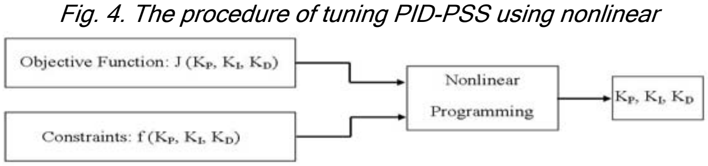


Table 2. Obtained parameters of PID-PSS using nonlinear programming.

PID Parameters	K_P	K_I	K_D
Obtained Value	48.8606	2.4665	10.8205

Simulation results

In this section, the designed PID-PSS is applied to the under study system (single machine infinite bus power system). To show effectiveness of the proposed PID-PSS, two other PSS designing methods are considered for comparing purposes. These methods are presented as following.

i. Classical lead-lag PSS based on phase compensation technique (CPSS)

ii. Robust PSS based on quantitative feedback theory (QFT-PSS)

The detailed step-by-step procedure for computing the parameters of the classical lead-lag PSS (CPSS) using phase compensation technique is presented in (Kundur, 1993). Here, the CPSS has been designed and obtained as (13).

$$CPSS = \frac{35(0.3S+1)}{(0.1S+1)} \quad (13)$$

Also the washout filter, which essentially is a high pass filter, is used to reset the steady state offset in the output of the PSS. In this paper the value of the time constant is fixed to 10 sec and *Damping ratio=0.5* have been considered. Also the detailed step-by-step procedure to design the robust PSS based on the quantitative feedback theory (QFT-PSS) is presented in (Hemmati *et al.,* 2010). The QFT-PSS has been designed and obtained as (14).

$$QFT\text{-}PSS = \frac{30(0.42S+1)}{(0.045S+1)} \quad (14)$$

To study the controller performance under system uncertainties (controller robustness), three operating conditions are considered as follow:

1. Nominal operating condition
2. Heavy operating condition (20 % changing parameters from their typical values)
3. Very heavy operating condition (50 % changing parameters from their typical values)

In the nominal operating condition, the eigen values of the system with CPSS, QFT-PSS and PID-PSS are obtained and listed in Table 3. It is clear to see that the eigen values of the system with PID-PSS are farther than the imaginary axis and the system stability margin is more than other methods. To demonstrate the robustness performance of the proposed method, the performance index, the Integral of the Time multiplied Absolute value of the Error (*ITAE*), based on the system performance characteristics is defined as (15).

$$\mathrm{ITAE} = \int_0^t t|\Delta\omega|dt \quad (15)$$

Table 3. The eigen values of system with different PSSs.

PID-PSS	QFT-PSS	CPSS	Without PSS
-3.1503	-2.4549	-3.4256	-4.2797
-4.1278	-4.0626	-4.0503	-46.366
-4.5375	-46.3719	-46.3704	+0.1009 + j4.758
-46.3736	-9.886 + j93.103	-3.2991 + j57.32	+0.1009 - j4.758
-335.1202	-9.886 - j93.103	-3.2991 - j57.32	

Where the parameter "t" is the simulation time and the time period for simulation has been considered from zero to 100 seconds. It is worth mentioning that the lower the value of these indices, the better the system responses in terms of the time-domain characteristics. The *ITAE* is calculated following a 10% step change in the reference mechanical torque (ΔT_m) at all operating conditions (nominal, heavy & very heavy) and results are shown at Table 4. Following step change at ΔT_m, the PID-PSS has better performance than the other methods at all operating conditions. Where, the PID-PSS has lower *ITAE* index in comparison with CPSS and QFT-PSS, therefore the PID-PSS can damp power system oscillations more successfully. Also the PID-PSS has a robust performance under system uncertainties and with changing system operating condition from the nominal to very heavy, the PID-PSS *ITAE* index has the least changing in comparison with other methods. The PID controller is commonly used controller in the industry and this application of this new type PID-PSS can used in real world applications. Also the control effort signal is one of the most important factors to compare responses. The parameter ΔV_{ref} which is shown in Fig. 2 is the output of controller and is considered as the control effort signal. The control effort signal is computed as (16).

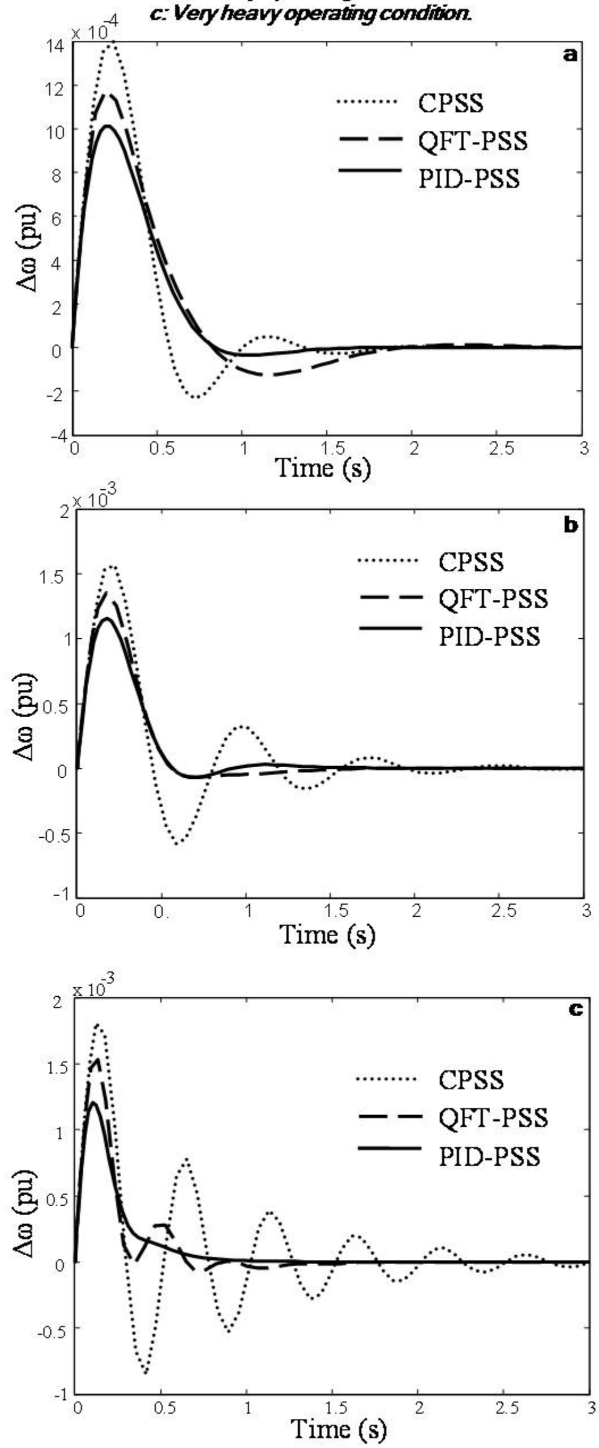
$$\mathrm{Control\_Effort} = \int_0^t t|\Delta \mathrm{Vref}|dt \quad (16)$$

Table 4. The calculated ITAE.

	ITAE		
	PID-PSS	QFT-PSS	CPSS
Nominal operating condition	4.4762×10^{-4}	5.5686×10^{-4}	5.7569×10^{-4}
Heavy operating condition	3.9055×10^{-4}	4.4080×10^{-4}	7.2451×10^{-4}
Very heavy operating condition	2.9213×10^{-4}	3.4774×10^{-4}	8.9021×10^{-4}

The control effort has been calculated following a 10% step change in the reference mechanical torque (ΔT_m) at all operating conditions (nominal, heavy & very heavy) and results are shown at Table 5. It is clear to see that following step change at ΔT_m, the PID-PSS has lower control effort than the other methods at all operating

Fig. 5. Dynamic responses Δω following 0.1 step increase in the reference mechanical torque (ΔTm) a: Nominal operating condition b: Heavy operating condition c: Very heavy operating condition.



conditions. This means that the PID-PSS damps power system oscillations by injecting lower control signal. In the other hands the controller with lower control effort signal is equal with lower cost for implementation. Also the PID-PSS has robust properties such as robust control techniques. This characteristic is due to differential section of controller which performs such as a damping factor.

Table 5. The calculated control effort signal.

Control effort signal			
	PID-PSS	QFT-PSS	CPSS
Nominal operating condition	0.0293	0.0308	0.0327
Heavy operating condition	0.0333	0.0334	0.0490
Very heavy operating condition	0.0276	0.0421	0.0721

Although the control effort and performance index results are enough to compare the methods, but it can be more useful to show responses in figures. Fig. 5 shows $\Delta\omega$ at nominal, heavy and very heavy operating conditions following 10% step change in the reference mechanical torque (ΔT_m). It is clear to see that between all operating conditions, the PID-PSS has better performance than the other methods in mitigating oscillations. Also between QFT-PSS and CPSS, the QFT-PSS has better performance than CPSS.

Conclusions

In this paper a new nonlinear robust PSS with PID configuration based on pole placement and nonlinear programming methods has been successfully proposed. The proposed method was applied to a typical single machine infinite bus power system containing system parametric uncertainties and various loading conditions. Eigen value analysis and time domain simulation results demonstrate the effectiveness of the proposed algorithm. The simulation results demonstrated that the designed PID-PSS guarantee robust stability and robust performance under a wide range of loading conditions. Beside the proposed PID-PSS was compared with a robust PSS and the results showed that the proposed PSS has a better performance than robust PSSs.

The nominal parameters and operating conditions of the system are listed in Table 6.

Table 6. The nominal system parameters.

Generator	M = 10 Mj/MVA	T'_{do} = 7.5 s	X_d = 1.68 p.u.
	X_q = 1.6 p.u.	X´d = 0.3 p.u.	D = 0
Excitation system		K_a = 50	T_a = 0.02 s
Transformer		X_{tr} = 0.1 p.u.	
Transmission lines	X_{te1} = 0.5 p.u.	X_{te2} = 0.9 p.u.	
Operating condition	V_t =1.03 p.u.	P=0.95 p.u.	Q=0.1 p.u.

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