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QFT Based Controller Design of Thyristor-Controlled Phase Shifter for Power System Stability Enhancement

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ABSTRACT: This paper presents the automatic design method for a thyristor-controlled phase shifter (TCPS) controller based on quantitative feedback theory (QFT) to improve power system stability in spite of system uncertainties and various disturbances. A genetic algorithm (GA) in a loop shaping state of QFT design has been used to design the TCPS controller satisfying all QFT bounds without repetition of a manual try and error. The proposed performance index in GA has been composed of the QFT bounds and the damping ratio. To verify control performance of the proposed TCPS controller based on QFT using GA, the closed loop eigenvalue and the damping of power system have been analyzed and nonlinear simulations for a single machine infinite bus system have been performed under various disturbances for various operating conditions. The control characteristics of the proposed TCPS controller have been compared with that of the conventional power system stabilizer (PSS) and conventional TCPC controller. The simulation results show that the proposed TCPS controller provided better dynamic responses in comparison with the conventional PSS and TCPS controller.
Keywords: Quantitative feedback theory(QFT), genetic algorithm(GA), thyristor-controlled phase shifter (TCPS), robust control, power system stabilizer (PSS).

I. INTRODUCTION

The complicatedly interconnected power systems have a small signal oscillatory instability characteristics caused by insufficient natural damping in the system. A power system stabilizer (PSS) has been widely utilized to damp low frequency oscillation and to improve small signal stability through the supplementary excitation control of a generator [1-4]. However, a PSS may cause great variations in the voltage profile, may result in leading power factor and may not be able to suppress oscillation resulting from severe disturbance [5]. With the recent advances in power electronics technology, the flexible AC transmission system (FACTS) devices have been installed to enhance power system stability, such as thyristor-controlled series capacitor (TCSC)[6], static var compensator (SVC)[7], thyristor-controlled phase shifter (TCPS)[8], unified power flow controller (UPFC) [9] and static synchronous compensator (STATCOM) [10]. The application of supplementary controllers for the FACTS devices which use reliable and high speed power electronic devices can considerably improve system damping and can also improve the system voltage profile, which is advantageous over a PSS [5]. As one of the FACTS devices, several approaches for a TCPS have been applied to damping controller design in power system [11-18]. The TCPS provides an alternative to the conventional PSS in suppressing power system oscillations and is of particular importance to the power system where a PSS cannot be properly installed for reasons such as the system voltage profile, the unsuitability of the generator and so on [12].

In this paper, the TCPS controller has been designed to damp low frequency oscillation of the power system and to enhance power systems stability. However, the power systems have system uncertainties due to various generating and loading conditions, variation of system parameters and system nonlinearity, etc. The increase of these uncertainties makes the optimal control of the power system difficult. The TCPS controller design without considering system uncertainties may fail to operate and stabilize the power system. In order to improve the robustness of the TCPS controller against system uncertainties, this paper focuses on a robust controller design of the TCPS using quantitative feedback theory (QFT) [19-20]. The try-and-error loop shaping procedure in QFT design make it difficult to design the controller to satisfy all specifications. This also makes it high order controller. In order to design a structure-specified low-order controller that satisfies all QFT bounds, the automatic loop shaping has been performed using a genetic algorithm (GA) [21]. The dynamic characteristic responses by means of time domain simulations have been investigated to verify the robustness of the TCPS controller based on QFT under various operating conditions. The control characteristics of the proposed TCPS controller have been compared with that of the simulated annealing based PSS (SA-PSS) [8] and the SA based TCPC (SA-TCPS)[8] controller. The simulation results show that the proposed TCPS controller provided better dynamic responses in comparison with the SA-PSS and SA-TCPS controller.

II. POWER SYSTEM MODEL

2.1 Generator and exciter

Fig. 1 shows the single machine infinite bus power system which has the TCPS and local load admittance Y in a generator bus, and transmission line impedance Z [8][15]. The generator with the IEEE Type-ST1 excitation system is modeled by four first-order nonlinear differential equations as following equations [3].

$$\frac{d}{dt}\omega = P_m - P_e - D(\omega - 1))/M \tag{1}$$

$$\frac{d}{dt}\delta = \omega_b(\omega - 1) \tag{2}$$

$$\frac{d}{dt}E_q' = (E_{fd} - (x_d - x_d')i_d - E_q')/T_{d0}' \tag{3}$$

$$\frac{d}{dt}E_{fd} = (K_A(V_{ref} - v_t + u_E) - E_{fd})/T_A \tag{4}$$

where ω is the rotor speed, ω_b is the synchronous speed and δ the rotor angle. M is inertia constant, D is damping coefficient, T_{do}' is the open circuit field time constant and E_q' is internal voltage. E_{fd} is the field voltage, v_t is terminal voltage and u_E is PSS control input.

The output electric power equation of generator is given by

$$P_e = v_d i_d + v_q i_q \tag{5}$$

where,

$$v_t = (v_d^2 + v_q^2)^{1/2} \tag{6}$$

$$v_d = x_q i_q \tag{7}$$

$$v_q = E_q' - x_d' i_d \tag{8}$$

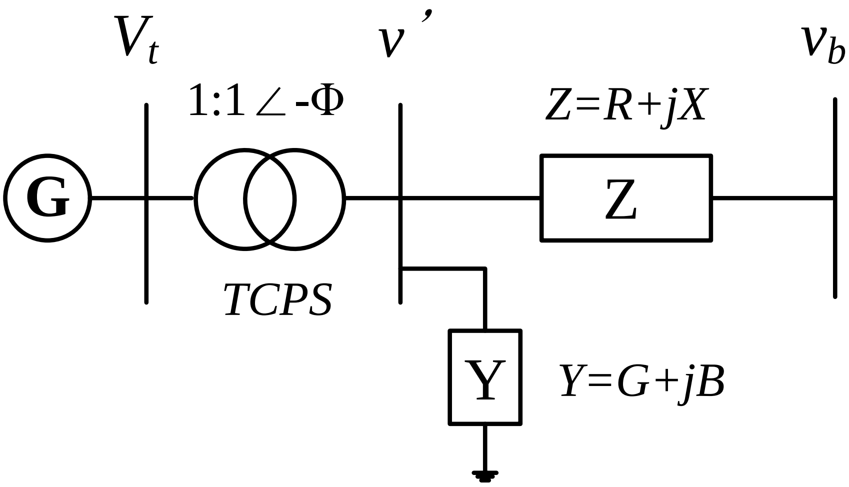


Fig. 1. Single machine infinite bus system with a TCPS

2.2 TCPS model

Fig. 2 shows the configuration of a TCPS [11][13][15]. The basic function of a TCPS is to control transmission line power flow through the modulation of the phase angle difference between the two sides of the transmission line voltage. The voltage at the end bus of TCPS v' is phase shifted with respect to the input voltage v_t by angle Φ as shown in Fig. 2[15].

The TCPS in Fig. 1 has a ratio of 1:1 $\angle -\Phi$. The real power flow is obtained by

$$P_e = \frac{E_q' v_b}{X}\sin(\delta - \Phi) \tag{9}$$

where Φ is phase shift angle of the TCPS. The TCPS can control the relative phase angle between the system voltage by adjusting the angle Φ. The phase shift angle of the TCPS, Φ, can be modeled by the first order transfer function and can be written as following equation [8][17].

$$\frac{d}{dt}\Phi = (K_S(\Phi_{ref} - u_{TCPS}) - \Phi)/T_S \tag{10}$$

where Φ_{ref} is the reference angle, and T_S and K_S are the gain and time constant of the TCPS respectively.

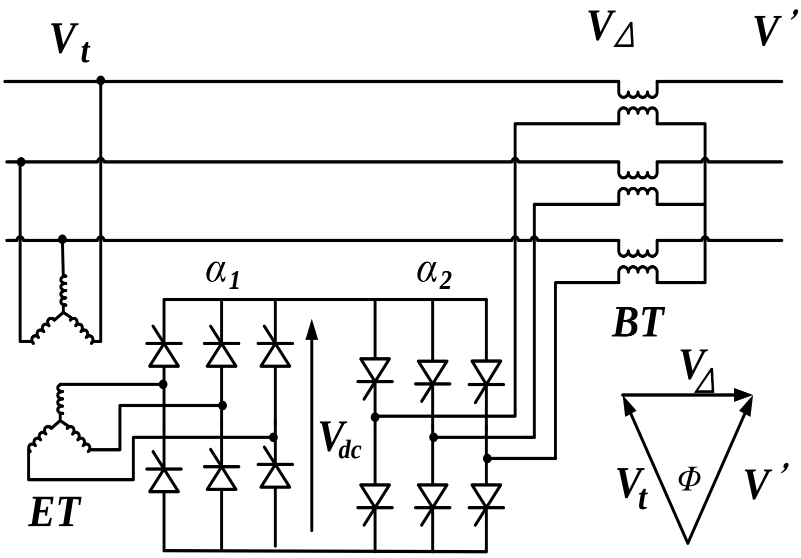


Fig. 2.Configuration of TCPS

2.3 Linearized model

To design QFT based controller, the linearized model around a nominal operating point is needed. The detail procedure is in [8]. The linearized equation to nonlinear differential equations such as (1)~(4) and (10) including the generator, excitation system and TCPS can be expressed by

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{11}$$

where,

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_p}{M} \\ -\frac{K_4}{T_{do}'} & 0 & -\frac{K_3}{T_{do}'} & \frac{1}{T_{do}'} & -\frac{K_q}{T_{do}'} \\ -\frac{K_5 K_A}{T_A} & 0 & -\frac{K_6 K_A}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_v}{T_A} \\ 0 & 0 & 0 & 0 & -\frac{1}{T_A} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{K_S}{T_S} \end{bmatrix}$$

$\Delta x = [\Delta\delta, \Delta\omega, \Delta E_q', \Delta E_{fd}, \Delta\Phi]^T$, $\Delta u = [u_{TCPS}]$.

Δx and Δu are the state and control vector respectively. A and B are constant matrices which depend on system parameters and the operating point. The parameters $K_1 \sim K_6$, K_p, K_q and K_v are computed in operating condition.

The block diagram of the linearized power system is shown in Fig. 3 [8][17].

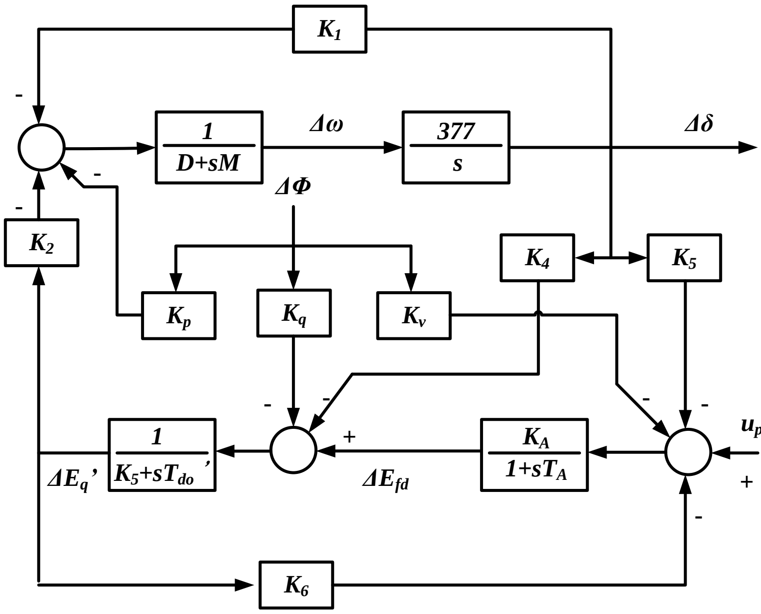


Fig. 3.Block diagram of the linearized power system model

III. DESIGN OF TCPS CONTROLLER BASED ON QFT USING GA

3.1 QFT overview [19]

The basic procedure of a conventional QFT design is as follow. First step for a QFT design is to convert the target performance specifications of the closed loop system and the system uncertainty into QFT bounds. Then the controller $K_{TCPS}(s)$ is designed by using the gain-phase loop shaping technique until the nominal open loop transfer function $L_o(s) = G_o(S)K_{TCPS}(s)$ satisfied the QFT bounds at all selected frequency as shown in Fig. 4. However the loop shaping method is usually performed manually. The procedure is a trial and error method which inserts or manipulates gain, poles and zeros in the nominal open loop transfer function of system.

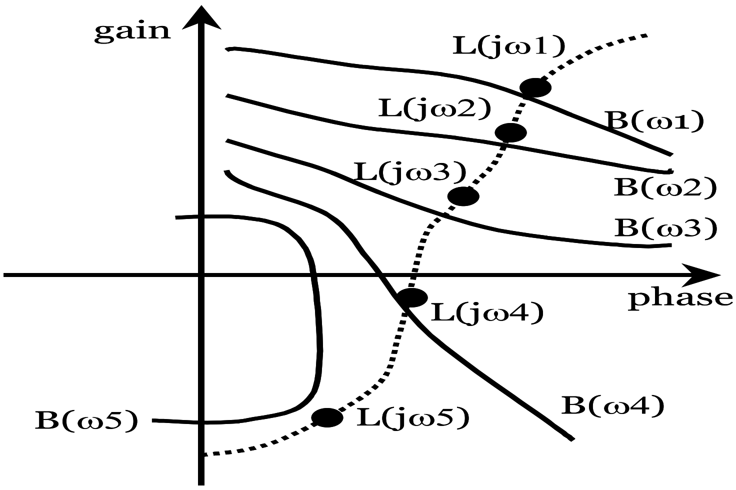


Fig. 4. QFT bounds and $L_0(s)$

3.2 Procedure of TCPS controller design based on QFT using GA

To design the TCPS controller based on QFT, the parameter uncertainty must be selected. Then we can get the transfer function for the uncertain plant sets $G(S) \in$ G. The ranges of the active power and reactive power in this paper are chosen as follows.

$$0.7 \le P_e \le 1.3,\ -0.2 \le Q_e \le 0.2 \tag{12}$$

After selecting the uncertain plant sets, the frequency points are selected as follows.

$$\omega_i = [0.1, 1, 2, 3, 4, 5, 6, 7, 8, 10, 50, 100] \text{ rad/sec} \tag{13}$$

The plant templates of the uncertain plant sets $G(j\omega_i)$ are calculated at the selected all frequency points ω_i. And an arbitrary stable transfer function in the plant sets is chosen as the nominal plant $G_o(s)$. And after selecting the robust stability and disturbance attenuation specifications, QFT bounds are calculated at all frequency points ω_i. The robust stability and disturbance attenuation specifications are defined as follows

$$\left|\frac{L_0(j\omega)}{1+L_0(j\omega)}\right| \le 1.4 \tag{14}$$

$$\left|\frac{G(j\omega)}{1+L_0(j\omega)}\right| \le 0.011 \tag{15}$$

As the last stage for the TCPS controller design based on QFT, the loop shaping must be accomplished until QFT bounds at all frequency are satisfied and the closed-loop nominal system is stable. However, the manual loop shaping procedure is very difficult and takes long time. Therefore, the loop shaping procedure will be replaced by GA. To do this, the structure of the controller $K_{TCPS}(s)$ has been specified as shown in Fig. 5.

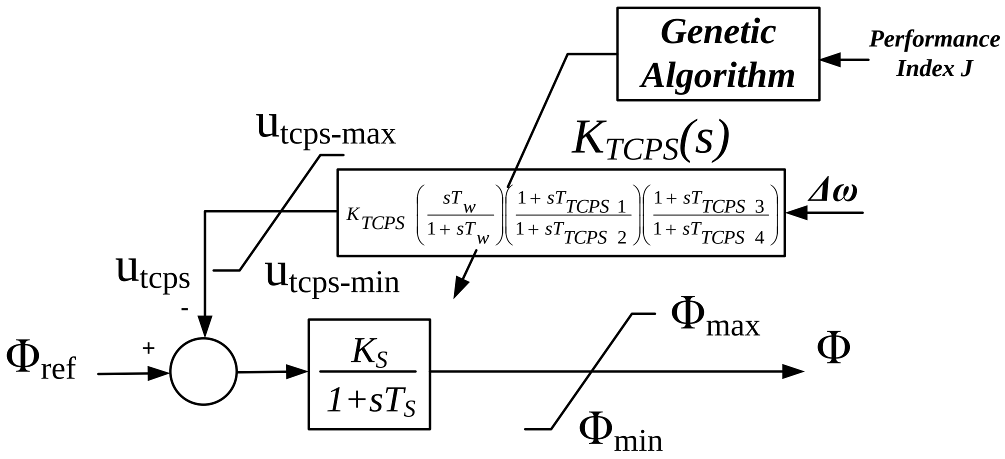


Fig. 5. A Block diagram for selecting the TCPS controller parameters using GA

The optimized parameters using GA are K_{TCPS}, T_w, T_{TCPS1}, T_{TCPS2}, T_{TCPS3} and T_{TCPS4} as shown in Fig. 5. In order to optimize these 6 parameters using GA, the objective function has been chosen as follows.

$$\min OJ = \alpha \, {}^{1}\!/_{J_{damp}} + \sum_{i=1}^{h} \beta_i J_{bound\_i} \tag{16}$$

where, α and $\beta_i (i = 1,2,3,\ldots,h)$ are the weighting values. J_{damp} is the damping ratio for the dominant oscillation mode and J_{bound_i} is defined as the bound index which checks QFT bound satisfaction at ω_i. Assuming that the eigenvalue corresponding to the dominant oscillation mode for the closed loop system is $\lambda = \xi + j\omega$, the damping ratio J_{damp} is given by,

$$J_{damp} = \frac{-\xi}{\sqrt{\xi^2 + \omega^2}} \tag{17}$$

The bound index J_{bound_i} is 0 if QFT bound at ω_i is satisfied, but 1 otherwise. The goal of this study is to minimize the objective function given by (16). If the eigenvalue of the closed loop system has the positive value, the system is unstable. Therefore the very large value is assigned to the performance index (18) by force. The fitness function for evaluating the each string in GA is the proposed performance index J .The performance index J used to select parameters of TCPS controller using the GA is defined as

$$Performance\ \ Index\ \ J = \frac{1}{\alpha\ {}^{1}\!/_{J_{damp}} + \sum_{i=1}^{h} \beta_i J_{bound\_i}} \tag{18}$$

IV. SIMULATION RESULTS

To select the parameters of the TCPS controller based on QFT as shown in Fig. 5, the real variable GA using the tournament selection method, the arithmetic crossover and the uniform mutation are used. The genetic algorithm optimization toolbox (GAOT) [21] has been used to optimize the parameters of the TCPS controller. The population size of the GA is 200 and the generation number is 200. The parameters of the designed TCPS controller based on QFT using GA are K_{TCPS} = 36.6552, T_w = 99.7840, T_{TCPS1} = 132.9217, T_{TCPS2} = 71.3789, T_{TCPS3} = 34.4548 and T_{TCPS4} = 19.9338.

Fig. 6 shows the loop shaping result using GA for the nominal open loop transfer function $L_0(s) = G_0(s)K_{TCPS}(s)$ according to ω_i . It is confirmed that the nominal open loop transfer function $L_o(s)$ satisfied all QFT bounds at all selected frequency as shown in Fig. 4.

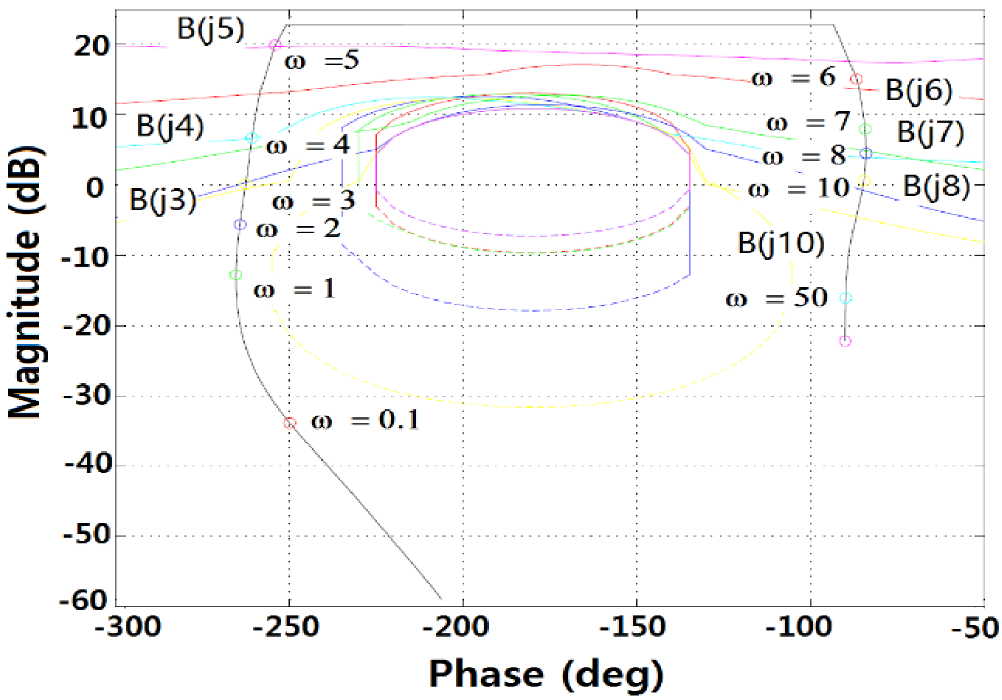


Fig. 6.QFT bounds and loop shaping result using GA

To verify the robust performance of the designed TCPS controller based on QFT using GA, the nonlinear simulations in time domain have been performed under the 3operating conditions of the power system. The proposed TCPS controller have been compared to those of the conventional simulated annealing based PSS (SA-PSS)[8] and the simulated annealing based TCPS (SA-TCPS) [8].The normal load condition is $P_e = 1$ (p.u.) and $Q_e = 0.015$ (p.u.), the leading PF load condition is $P_e = 0.7$ (p.u.) and $Q_e = -0.2$ (p.u.), and the heavy load condition is $P_e = 1.1$ [p.u.] and $Q_e = 0.4$ [p.u.]. The simulation constraints are $|\Phi| \le 10°$, $|u_{pss}| \le 0.2$(p.u.) and $|E_{fd}|$ ≤ 7.3 (p.u.). The system parameters are shown in Table. 1

Table 1. Power system parameters

Generator parameters	M=9.26, D=0, T_{do}'=7.76, x_d =0.973, x_d'=0.19, x_q =0.55
Exciter parameters	K_A =50, T_A =0.05
Line parameters	R=-0.034, X=0.997, G=0.249, B=0.262
TCPS parameters	K_S =1, T_S =0.05
Initial conditions	P_{e0} =1.0, Q_{e0} =0.015, V_{t0} =1.05

4.1 Normal load condition

Table 2 shows the eigenvalues and damping ratio of closed loop with the conventional SA-PSS, SA-TCPS and proposed TCPS respectively. The damping ratio with the proposed TCPS controller is improved in comparison with the conventional SA-PSS controller and the SA-TCPS controller. Fig. 7 shows the simulation results for angular velocity, rotor angle and terminal voltage with the SA-PSS, SA-TCPS and proposed TCPS under normal load in case that a 3-phase short circuit occurs near the infinite bus at 1.0s and is cleared at 1.1s without the power system configuration change. The first swing of angular velocity and rotor angle using the proposed TCPS controller is smaller than that using the conventional SA-PSS and SA-TCPS. The voltage profile is greatly improved with the SA-TCPS and proposed TCPS.

4.2Leading PF load condition

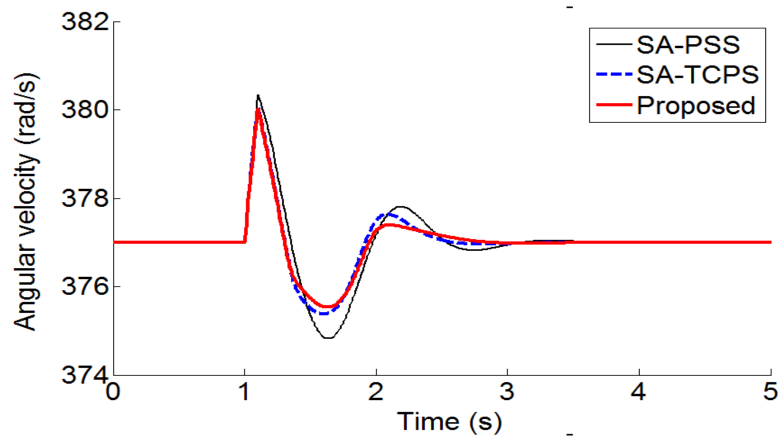
Fig. 8 shows the simulation results for angular velocity, rotor angle and terminal voltage with the SA-PSS, SA-TCPS and proposed TCPS under leading PF load in case that a 3-phase short circuit occurs near the infinite bus at 1.0s and is cleared at 1.1s without the power system configuration change. The first swing of angular velocity and rotor angle using the proposed TCPS controller is smaller than that using the conventional SA-PSS and SA-TCPS.

4.3 Heavy load condition

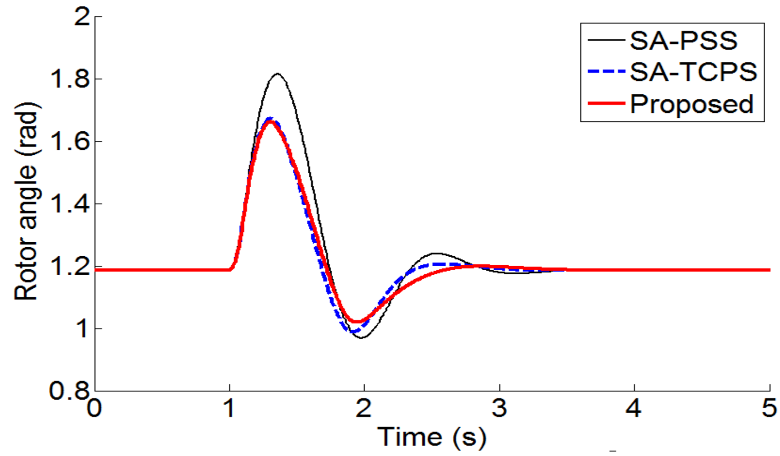
Fig. 9 shows the simulation results for angular velocity, rotor angle and terminal voltage with the SA-PSS, SA-TCPS and proposed TCPS under heavy load in case that a 3-phase short circuit occurs near the infinite bus at 1.0s and is cleared at 1.05s without the power system configuration change. The first swing of angular velocity and rotor angle using the proposed TCPS controller is smaller than that using the conventional SA-PSS and SA-TCPS.

Table 2. Eigenvalues and damping ratio

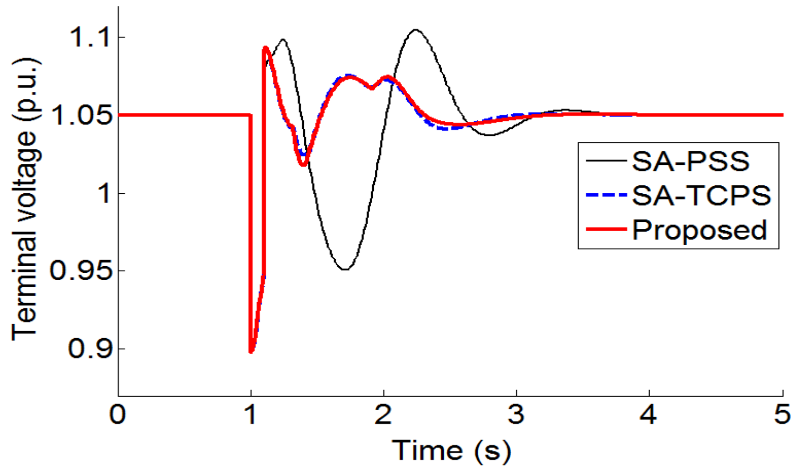
	Eigenvalues	Damping ratio
SA-PSS	-0.204, -8.439, -19.155 -2.776±5.042 -3.521±j6.406	1 0.482 0.482
SA-TCPS	-18.09, -0.209 -3.206±3.702 -6.67±j7.625 -11.171±0.917	1 0.655 0.658 0.997
Proposed TCPS	-2.768±j3.128 -9.435±j11.031 -15.788, -0.05, -0.014	0.663 0.650 1



(a) Angular velocity

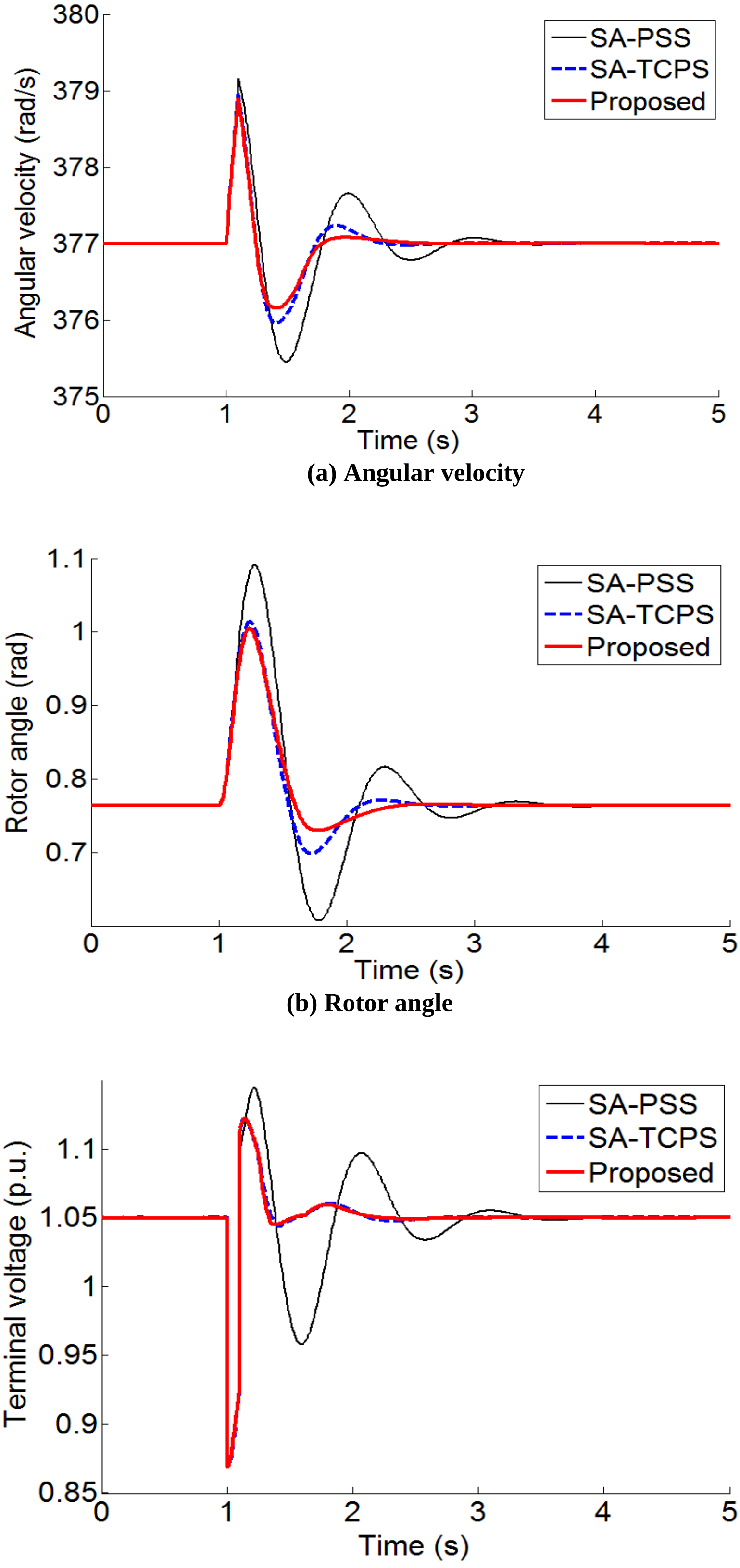


(b) Rotor angle



(c) Terminal voltage

Fig. 7. Dynamic responses in case that a 3-phase short circuit occurs near the infinite bus for 0.1s under normal load

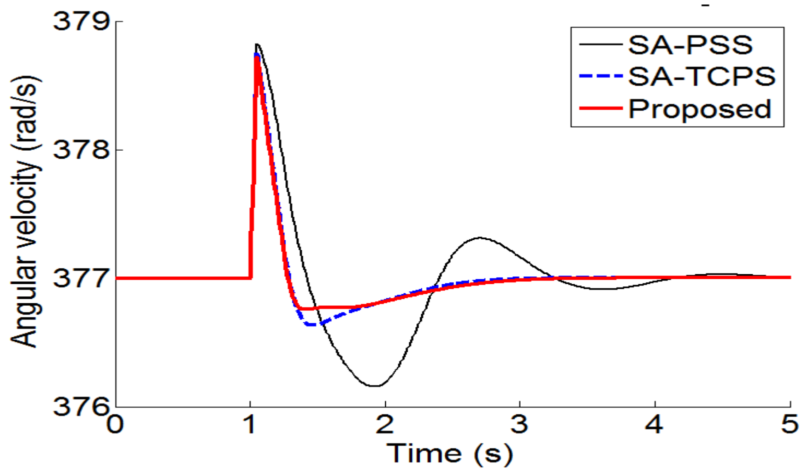


(a) Angular velocity

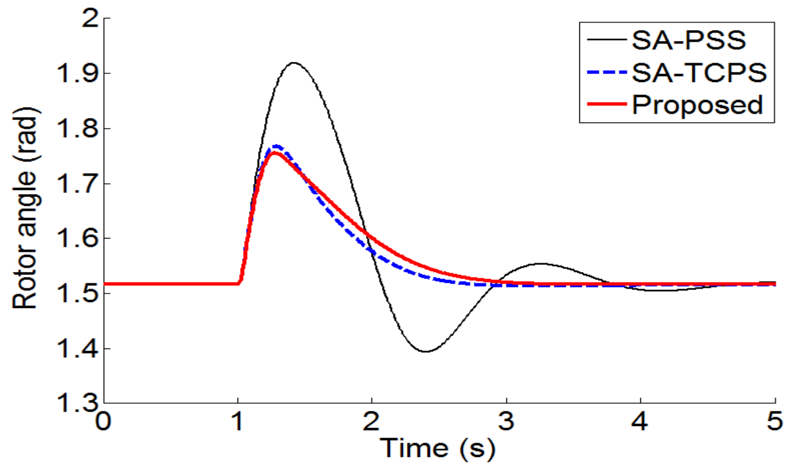
(b) Rotor angle

(c) Terminal voltage

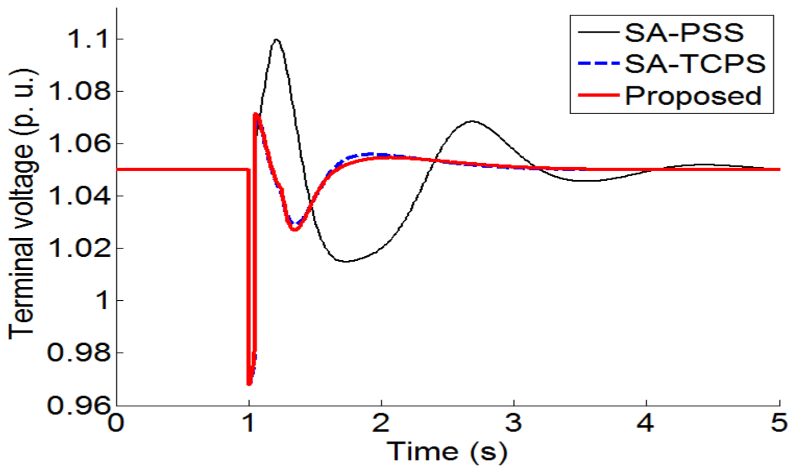
Fig. 8. Dynamic responses in case that a 3-phase short circuit occurs near the infinite bus for 0.1s under leading PF load



(a) Angular velocity



(b) Rotor angle



(c) Terminal voltage

Fig. 9. Dynamic responses in case that a 3-phase short circuit occurs near the infinite bus for 0.05s under heavy load

V. CONCLUSION

In this paper, the TCPS controller based on QFT using GA has been designed to enhance the power system stability. The QFT bounds and the damping ratio as the objective function of GA to select parameters of the TCPS controller has been used to design the robust controller. The robust performance of the proposed TCPS controller has been compared to those of the conventional SA-PSS and SA-TCPS. The main results in this paper are as follows.

① It is possible to automatically design the TCPS controller using the GA without a trial and error in loop shaping procedure.

② The simulation results show that the proposed TCPS controller endows better dynamic characteristics compared to that of conventional PSS.

③ The proposed TCPS controller can more significantly improve the voltage profile comparing with the conventional PSS.

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