Design and Application of a Nonlinear Coordinated Excitation and TCPS Controller in Power Systems

Ashfaque Ahmed Hashmani, Youyi Wang, and Tek Tjing Lie

Abstract: This paper presents a new approach to Thyristor Controlled Phase Shifter (TCPS) control. In this paper we have proposed a nonlinear coordinated generator excitation and TCPS controller to enhance the transient stability of a power system. The proposed controller is able to control three main parameters affecting a.c. power transmission: namely excitation voltage, phase angle and reactance in a coordinated manner. The TCPS is located at the midpoint of the transmission line. A nonlinear feedback control law is proposed to linearize and decouple the power system. The design of the proposed controller is based on the local measurements only. Simulation results have been shown to demonstrate the effectiveness of the proposed controller for the enhancement of transient stability of the power system under a large sudden fault.

Keywords: Excitation control, FACTS, phase angle and magnitude of the injected voltage, TCPS controller.

1. INTRODUCTION

Today, with the development of modern power system and increasing demand for power supply, the electric power industry is facing a great challenge in meeting the increased load demand with highest reliability and security by minimum transmission expenditure. More transmission lines are needed. However, due to the pressure of some practical factors such as environmental and cost considerations, power engineers can only depend on increasing the transmission capacities of the present transmission lines to meet the fast growth of energy demands. The Flexible AC Transmission Systems (FACTS) devices have helped in increasing the transmission capacities of the transmission lines. Therefore, the transmission lines are operating at high transmission levels. Due to these conditions, the stability margin of a power system has decreased significantly. Thus new techniques in power system control which can improve the dynamic performance and transient stability of power systems presents an even more formidable challenge. Fast controllers are needed to improve the transient stability of power systems. No doubt, excitation controllers are helpful in the enhancement of stability of power systems but the system stability may not be maintained when a large fault occurs close to the generator terminal [1].

A TCPS is a device that injects a variable series voltage to affect the power flow by modifying both the magnitude and the phase angle. Thus, the TCPS is essentially an equipment to modulate active power transmission in power systems. In addition, the TCPS can be employed to boost voltages in a power system [2]. The high speed of TCPS makes it attractive to be used to improve stability. Most of the existing research work in this field is focused on designing the controllers for the phase angle control [3,4,11] and not much attention has been paid to the control of both the phase angle and the magnitude of the injected voltage. The proposed paper will focus on that issue. With only excitation and phase angle control the stability of system can be obtained within certain range of fault location only and the system stability cannot be obtained when the fault occurs very close to the generator bus. The advantage of controlling both phase angle and magnitude of the injected voltage besides the excitation control is that the system stability can be obtained independent of the fault location. Through the fast control of the phase angle and the magnitude of the injected voltage, the TCPS is capable of controlling the active power flow through the transmission line and providing additional damping to power systems.

The generator excitation and TCPS controller is commonly designed by applying linear control theory. A linear controller may not be able to maintain sufficient stability when a large fault occurs. This is

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due to the fact that a power system is a highly nonlinear complex system. Moreover, when a large fault occurs, the behavior of the power system changes. Nonlinear controllers are suitable for the control and improvement of performance of power systems when operated under such conditions.

In this paper, a robust nonlinear coordinated generator excitation and TCPS controller is proposed to enhance the transient stability of a power system. The TCPS is located at the mid-point of the transmission line. A Direct Feedback Linearization (DFL) technique [5] has been used for determining the nonlinear feedback control law for the generator excitation. By the use of this technique, the power system model can be linearized and decoupled and that will help in designing the excitation and TCPS controller.

2. POWER SYSTEM MODEL

Consider a Single-Machine-Infinite-Bus (SMIB) power system model shown in Fig. 1.

The generator model is written as follows [6]:

$$\dot{\delta}(t) = \omega(t), \tag{1}$$

$$\dot{\omega}(t) = -\frac{D}{2H}\omega(t) + \frac{\omega_0}{2H}[P_m - P_e(t)], \tag{2}$$

$$\dot{E}_q'(t) = [k_c u_f(t) - E_q(t)]\frac{1}{T_{d0}'}, \tag{3}$$

where

$$E_q(t) = E_q' + (x_d - x_d')I_d(t), \tag{4}$$

$$P_e(t) = V_s Y_{12}' E_q'(t)\sin\delta(t), \tag{5}$$

$$Q_e(t) = E_q'(t) V_s Y_{12}' \cos\delta(t) - V_s^2 Y_{11}', \tag{6}$$

$$I_q(t) = \frac{P_e(t)}{E_q'(t)} = V_s Y_{12}' \sin\delta(t), \tag{7}$$

$$I_d(t) = \frac{-(Q_e(t) + V_s^2 Y_{11}' - E_q'^2(t) Y_{12}')}{E_q'(t)} = \frac{E_q'(t) V_s Y_{12}' \cos\delta(t) + E_q'^2(t) Y_{11}'}{E_q'(t)}. \tag{8}$$

The TCPS dynamic model for ϕ(t) [3] and k(t) can be expressed as follows:

$$\dot{\phi}(t) = \frac{1}{T_p}(-\phi(t) + \phi_o + k_p \mu_p(t)), \tag{9}$$

$$\dot{k}(t) = \frac{1}{T_k} - (k(t) - k_0 + k_k u_k(t)). \tag{10}$$

It can be assumed that a TCPS is installed in the power system between nodes a and b as shown in Fig. 2

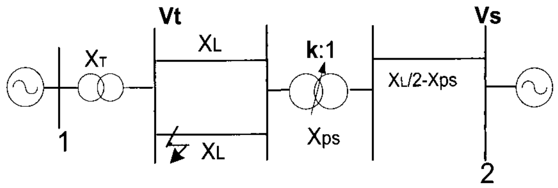

Fig. 1. An SMIB power system with a TCPS located at the middle of the transmission line.

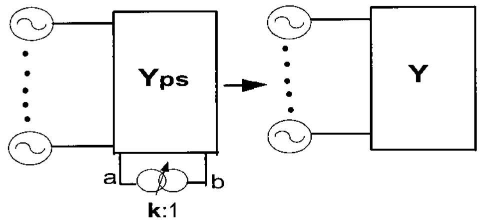

Fig. 2. The multimachine power system installed with a TCPS.

with k(t)=k∠ϕ. The relevant elements in the network admittance matrix are [7]:

$$Y_{aa} = Y_{aa}' + 1/Z_{ab}k^2, Y_{bb} = Y_{bb}' + 1/Z_{ab}, \quad Y_{ab} = -e^{-j\phi(t)}/Z_{ab}k, \ Y_{ba} = -e^{j\phi(t)}/Z_{ab}k. \tag{11}$$

The first step in forming the system admittance matrix, **Y**, which is obtained by deleting all nodes except the *n* generator internal nodes in the network admittance matrix of the power system, is to assume that the TCPS damping controller is initially not connected in the system. An initial system admittance matrix, $\mathbf{Y_{PS}}$, is first formed with the *n* generator internal nodes, and in addition the two nodes, nodes a and b, between which the TCPS is installed:

$$Y_{PS} = \begin{bmatrix} Y_K & Y_L \\ Y_{LT} & Y_M \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} Y_{aa} & Y_{ab} \\ Y_{ba} & Y_{bb} \end{bmatrix} & Y_L \\ Y_{LT} & Y_M \end{bmatrix}.$$

When the TCPS is connected to the power system, we know from (11) that the admittance matrix, $\mathbf{Y_K}$ can be expressed as follows:

$$Y_K = \begin{bmatrix} Y_{aa}(\mathrm{k},\phi) & Y_{ab}(\mathrm{k},\phi) \\ Y_{ba}(\mathrm{k},\phi) & Y_{bb}(\mathrm{k},\phi) \end{bmatrix}. \tag{12}$$

By deleting nodes a and b we can obtain the system admittance matrix as

$$Y = Y_M - Y_{LT} Y_K^{-1} Y_L. \tag{13}$$

It is evident from the (12)-(13) that after the insertion of the phase shifter the admittance matrix **Y** is no longer constant and it becomes the function of phase angle ϕ(t) and k(t). In this paper, we focus on controlling both ϕ(t) and k(t). Therefore when the TCPS is added to the power system, the admittance in power system model (1)-(8) will become a function of $\phi(t)$ and k(t).

The basic idea behind the phase shifter is to keep the transmitted power at a desired level independently of the power angle $\delta(t)$ in a predetermined operating range. In this way, the actual transmitted power can be increased significantly, even though the phase shifter does not increase the steady-state power transmission limit (but, it increases the transient and dynamic stabilities of the system) [8]. To keep the transmitted power at a desired level, the effective power angle [4] ($\delta(t)+\phi(t)$), can be kept constant by varying the parameter $\phi(t)$ [3-5]. When the fault occurs, the electrical power output of the generator will decrease, while the input mechanical power is constant. As a result, the rotor speed will increase and hence the power angle $\delta(t)$ will also increase. Therefore, to maintain the effective power angle ($\delta(t)+\phi(t)$) constant, the value of $\phi(t)$ should be decreased. In addition to the phase angle control, the control of magnitude of the injected voltage is also helpful in keeping the transmitted power at a desired level.

3. FEEDBACK LINEARIZATION

In this section, the design principles using the Direct Feedback Linearization (DFL) technique to design a nonlinear controller for the power system shown in Fig. 1 are discussed. To eliminate the nonlinearities in the equations given in Section 2, we first eliminate $E_q^{'}(t)$ in the generator electrical dynamics by differentiating the active power $P_e(t)$ of (5) as follows:

$$\dot{P}_e(t) = V_s\dot{E}_q^{'}(t)Y_{12}^{'}\sin(\delta(t)) + V_sE_q^{'}(t)Y_{12}^{'}\cos(\delta(t))\dot{\delta}(t),$$

since $\dot{\delta}(t)=\omega(t)$, therefore,

$$\dot{P}_e(t) = V_s\dot{E}_q^{'}(t)Y_{12}^{'}\sin(\delta(t)) + V_sE_q^{'}(t)Y_{12}^{'}\cos(\delta(t))\omega(t).$$

Using (3)-(4) and (7)- (8), we have

$$\dot{P}_e(t) = \frac{1}{T_{do}^{'}}[k_cu_f(t)I_q(t) - P_e(t) - (x_d - x_d^{'})I_d(t)I_q(t)] + \omega(t)[Q_e(t) + V_s^2Y_{11}^{'}].$$

Let $\Delta P_e(t) = P_e(t) - P_m$, then

$$\Delta\dot{P}_e(t) = \frac{1}{T_{do}^{'}}[k_cu_f(t)I_q(t) - (\Delta P_e(t) + P_m) - (x_d - x_d^{'})I_d(t)I_q(t)] + \omega(t)[Q_e(t) + V_s^2Y_{11}^{'}].$$

If we let

$$v_f(t) = [k_cu_f(t)I_q(t) - (x_d - x_d^{'})I_d(t)I_q(t) - P_m] + \omega(t)[Q_e(t) + V_s^2Y_{11}^{'}]T_{d0}^{'}, \tag{14}$$

then,

$$\Delta\dot{P}_e(t) = -\frac{1}{T_{d0}^{'}}\Delta P_e(t) + \frac{1}{T_{d0}^{'}}v_f(t). \tag{15}$$

The model (1)-(3) then has been linearized. The linearized model is:

$$\Delta\dot{\delta}(t) = \omega(t), \tag{16}$$

$$\dot{\omega}(t) = -\frac{D}{2H}\omega(t) - \frac{\omega_0}{2H}[P_m - P_e(t)], \tag{17}$$

$$\Delta\dot{P}_e(t) = -\frac{1}{T_{d0}^{'}}\Delta P_e(t) + \frac{1}{T_{d0}^{'}}v_f(t), \tag{18}$$

where $v_f(t)$ is the new input of the excitation loop of the generator. Note that the mapping (14) from $u_f(t)$ to $v_f(t)$ is invertable, except when $I_q(t)=0$ (which is not in the normal working region for a generator). From (14) the following DFL compensating law can be obtained:

$$u_f(t) = \frac{1}{k_cI_q(t)}[v_f(t) - \omega(t)T_{d0}^{'}\{Q_e(t) + V_s^2Y_{11}^{'}\} + (x_d - x_d^{'})I_q(t)I_d(t) + P_m]. \tag{19}$$

Remark 3.1: From the analysis given above, the compensating law (19) is practically realizable and the linearization is of the whole working region. Using the nonlinear compensating law (19) we can linearize the power system model through the excitation loop.

Remark 3.2: Although in this paper we have considered a simplified model but the DFL technique can be extended to multimachine case.

When a large sudden fault occurs, the interconnection parameters such as the equivalent reactance of the transmission line will change suddenly and due to this the system can lose synchronism. In the next section a robust control design technique is introduced to improve the transient stability of the power system.

4. ROBUST FEEDBACK CONTROLLER DESIGN

In this section, the design procedure for our proposed excitation and TCPS controller is presented. When the parameters in the power system are known, the DFL control law can be designed to linearize the plant. But when a large sudden fault occurs the reactance of the transmission line x_L varies very much and hence $Y_{12}^{'}$, Y_{12} and $Y_{11}^{'}$ will also change. These variations are treated as parametric uncertainties.

Considering the uncertainty in x_L, the plant model becomes:

$$\Delta\dot{\delta}(t) = \omega(t), \tag{20}$$

$$\dot{\omega}(t) = -\frac{D}{2H}\omega(t) - \frac{\omega_0}{2H}[P_m - P_e(t)], \tag{21}$$

$$\begin{aligned}\Delta\dot{P}_e(t) = &-[\frac{1}{T_{d0}^{'}} + \mu(t)]\Delta P_e(t) \\ &+[\frac{1}{T_{d0}^{'}} + \mu(t)][k_c u_f(t) I_q(t) \\ &-(x_d - x_d^{'}) I_d(t) I_q(t) - P_m \\ &+(T_{d0}^{'} + \Delta T_{d0}^{'})\omega(t) Q_e(t) \\ &+(\overline{T}_{d0}^{'} + \Delta\overline{T}_{d0}^{'})\omega(t)],\end{aligned} \tag{22}$$

where $\mu(t) = \frac{1}{T_{d0}^{'}} - \frac{1}{T_{d0}^{'} + \Delta T_{d0}^{'}}$,

$$\Delta T_{d0}^{'} = \frac{x_{12}^{'} + \Delta x_L}{x_{12} + \Delta x_L} T_{d0}^{'} - \frac{x_{12}^{'}}{x_{12}} T_{d0}^{'} ,$$

$x_{12}^{'} = \frac{1}{Y_{12}^{'}}$ and $x_{12} = \frac{1}{Y_{12}}$.

Δx_L indicates the uncertainty in x_L and

$\overline{T}_{d0}^{'} = T_{d0}^{'} Y_{11}^{'} V_s^{2}$.

Let

$$\begin{aligned}v_f(t) = &k_c u_f(t) I_q(t) \\ &-(x_d - x_d^{'}) I_d(t) I_q(t) \\ &+T_{d0}^{'}\omega(t) Q_e(t) + \overline{T}_{d0}^{'}\omega(t) - P_m,\end{aligned} \tag{23}$$

then, the power system model (20)-(22) becomes,

$$\Delta\dot{\delta}(t) = \omega(t), \tag{24}$$

$$\dot{\omega}(t) = -\frac{D}{2H}\omega(t) - \frac{\omega_0}{2H}[P_m - P_e(t)], \tag{25}$$

$$\begin{aligned}\Delta\dot{P}_e(t) = &-[\frac{1}{T_{d0}^{'}} + \mu(t)]\Delta P_e(t) \\ &+[\frac{1}{T_{d0}^{'}} + \mu(t)]v_f(t) \\ &+[\frac{1}{T_{d0}^{'}} + \mu(t)]\Delta T_{d0}^{'}\omega(t) Q_e(t) \\ &+[\frac{1}{T_{d0}^{'}} + \mu(t)]\Delta\overline{T}_{d0}^{'}\omega(t).\end{aligned} \tag{26}$$

Choosing the state as

$$x^T(t) = [\Delta\delta(t) \quad \omega(t) \quad \Delta P_e(t)],$$

(24)-(26) can be rewritten as follows:

$$\dot{x}(t) = (A + \Delta A)x(t) + (B + \Delta B)v_f(t), \tag{27}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{D}{2H} & -\frac{\omega_0}{2H} \\ 0 & 0 & -\frac{1}{T_{d0}^{'}} \end{bmatrix}, \quad \Delta A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \beta & -\mu(t) \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 0 & \frac{1}{T_{d0}^{'}} \end{bmatrix}^T, \quad \Delta B = \begin{bmatrix} 0 & 0 & \mu(t) \end{bmatrix}^T,$$

$$\beta = \left[\frac{1}{T_{d0}^{'}} + \mu(t)\right]\left[\Delta\overline{T}_{d0}^{'} + \Delta T_{d0}^{'} Q_e(t)\right],$$

$\mu(t), \Delta T_{d0}^{'}, \Delta\overline{T}_{d0}^{'}$ are bounded and therefore, β also.

The parametric uncertainties $\Delta A(t)$ and $\Delta B(t)$ can be expressed as follows:

$$[\Delta A(t), \Delta B(t)] = DF(t)[E_1, E_2],$$

where D, E_1, and E_2 are constant matrices given as follows:

$$D = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T, E_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{|\beta|}{\gamma} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$E_2 = \begin{bmatrix} 0 & 0 & -1 \end{bmatrix}^T,$$

$$F(t) = \begin{bmatrix} 0 & \gamma\frac{\beta(t)}{|\beta|} & -\mu(t) \end{bmatrix} \text{ and}$$

$$F^T(t)F(t) \le \alpha^2 I (\alpha > 0);$$

γ is a constant.

It is clear from the above analysis that the DFL control law (23) is valid in the whole practical operating working region, except when $I_q(t) = 0$. For $I_q(t) = 0$, from (7), we know that the power angle $\delta(t)$ will be 0^o or 180^o. At normal operating point the power angle is between 0^o and 180^o. Normally, if the power angle reaches 180^o, it is not possible to maintain synchronism.

To design a robust control law $u_f(t)$ to stabilize the power system model (1)-(8) with uncertainties is equivalent to design a robust control law $v_f(t)$ to stabilize the linearized plant (27).

To solve the robust control problem for the DFL compensated generator model (27) involves solving the following algebraic Riccati equation [9,10]:

$$(A - BR^{-1}E_2^T E_1)^T P + P(A - BR^{-1}E_2^T E_1) + P(\alpha^2 DD^T - BR^{-1}B^T)P + E_1^T (I - E_2 R^{-1} E_2^T) E_1 = 0, \quad (28)$$

where $R = E_2^T E_2 > 0$.

Thus, the power system (1)-(8) under a symmetrical 3-phase short-circuit fault is transiently stable via the nonlinear DFL control law:

$$u_f(t) = \frac{1}{k_c I_q(t)} \{ v_f(t) + (x_d - x_d^{'}) I_d(t) I_q(t) - T_{d0}^{'} \omega(t) Q_e(t) - \bar{T}_{d0}^{'} \omega(t) + P_m \}, \quad (29)$$

and $v_f(t) = -R^{-1}(B^T P + E_2^T E_1) x(t)$, (30)

if and only if there exist a stabilizing solution $P \geq 0$ for the Riccati equation (28). The power system (1)-(8) is transiently stable via the control law (29)-(30) means that the power system under a symmetrical 3-phase short-circuit fault will not be out of synchronism. Also, in the postfault period,

$$\lim_{t\to\infty} |\Delta\delta(t)| = 0, \quad \lim_{t\to\infty} |\omega(t)| = 0, \quad \lim_{t\to\infty} |\Delta P_e(t)| = 0.$$

From (30), we have

$$v_f(t) = -k_1 \Delta\delta(t) - k_2 \omega(t) - k_3 \Delta P_e(t), \quad (31)$$

where $[k_1, k_2, k_3] = R^{-1}(B^T P + E_2^T E_1)$.

Remark 4.1: Since the physical limit of the excitation voltage has been considered, in the case where a symmetrical 3-phase short-circuit fault occurs on one of the transmission lines (for λ not too small), the robust control system maintains transient stability of the power system in some cases. The smallest value of λ for which the transient stability is retained can be found by simulation.

Since the TCPS model (9)- (10) is linear, the pole-assignment control design approach is employed to find the feedback control laws. When a fault occurs, the TCPS can be helpful in maintaining the power system stability besides the excitation controller.

The control law for the TCPS (for the phase angle control) is as follows:

$$u_p(t) = -K x_p(t),$$

where $K = [K_1 \quad K_2]$,

$x_p(t) = [\Delta\phi(t) \quad \omega_L(t)]^T$ and $\Delta\phi = \phi(t) - \phi_0$.

Using the parameters $T_p = 0.25$ sec. and $k_p = 1$ for the TCPS, the robust controller gain for the TCPS is found as $K = [10 \quad 5]$.

Thus, the control law for phase angle control for the TCPS can be expressed as:

$$u_p(t) = -10\Delta\phi - 5\omega_L(t).$$

The control law for the TCPS (for the control of the magnitude of the injected voltage) is as follows:

$$u_k(t) = -K x_k(t),$$

where $K = [K_3 \quad K_4]$ and $x_k(t) = [k(t) \quad \omega_L(t)]^T$.

Using the parameters $T_k = 0.06$ sec., $k_k = 1$ and $k_0 = 1.0$ for the TCPS, the robust controller gain for the TCPS is found as $K = [5 \quad -14]$.

Thus, the control law for control of the magnitude of injected voltage for the TCPS can be expressed as:

$$u_k(t) = -5k(t) + 14\omega_L(t).$$

The excitation controller can be coordinated with the TCPS controller because for the design of the excitation controller only the bounded values have been considered. The design of the controllers for the generator and the TCPS is independent of each other since the feedback linearization technique applied decouples the power system model. Only the local measurements are used for the controller design.

5. SIMULATION RESULTS

Consider the generator model (20)-(22) and the DFL control law (29) and (31). Example system parameters and physical limits used in the simulation are as follows:

ω_0 =314.159 rad/sec.; D =5.0 p.u.; H=4.0 sec.; $T_{d0}^{'}$ =6.9 sec.; kc=1; xd=1.863 p.u.; $x_d^{'}$ =0.257p.u.; xT =0.127 p.u.; $x_L = 0.2426$ p.u.

The physical limit for the excitation voltage is max. $|k_c u_f(t)|$ =4.8 p.u., for the phase shift angle it is $-10^0 \leq \phi(t) \leq 10^0$ and for k(t) it is $0.9 \leq k(t) \leq 1$.

The operating point considered is $\delta 0 = 78^o$; $Pm = 0.95$ *p.u.*; $\Delta\omega = 0.0$ *rad./sec.*

The fault considered is a symmetrical three-phase short-circuit fault that occurs on a transmission line as shown in Fig. 1.

In the simulation conducted, the following fault sequence has been considered.

Fault Sequence:

Stage 1: The system is in prefault steady state,

Stage 2: A fault occurs at t = 0.1 sec,

Stage 3: The fault is removed and the transmission lines are restored with the fault cleared at t = 0.2sec,

Stage 4: The system is in a postfault-state.

From the system shown in Fig. 1 with the system parameters given above and (27), the following can be obtained:

$$A=\begin{bmatrix}0 & 1 & 0\\ 0 & -0.625 & -39.2699\\ 0 & 0 & -0.14493\end{bmatrix},$$

$$\Delta A=\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & \beta & -\mu(t)\end{bmatrix}, B=\begin{bmatrix}0 & 0 & 0.14493\end{bmatrix},$$

$$\Delta B=\begin{bmatrix}0 & 0 & \mu(t)\end{bmatrix}^T$$

and $\beta=\left[\frac{1}{T'_{d0}}+\mu(t)\right]\left[\Delta\overline{T}'_{d0}+\Delta T'_{d0}Q_e(t)\right]$.

Thus, $-0.013\le|\mu(t)|\le 0.0068$, $-0.5605\le\left|\Delta T'_{d0}\right|\le 0.3378$, $-1.734\le\left|\Delta\overline{T}'_{d0}\right|\le 1.733$, $-0.3175\le|\beta|\le 0.3245$.

Choosing $D=\begin{bmatrix}0 & 0 & 1\end{bmatrix}^T$, $E_1=\begin{bmatrix}1 & 0 & 0\\ 0 & \frac{|\beta|}{\gamma} & 0\\ 0 & 0 & 1\end{bmatrix}$,

$E_2=\begin{bmatrix}0 & 0 & -1\end{bmatrix}^T$, $F(t)=\begin{bmatrix}0 & \gamma\frac{\beta(t)}{|\beta|} & -\mu(t)\end{bmatrix}$,

$\gamma = 0.0068$ *and* $\alpha 2=2(0.0068)2>0$. We have

$$R=E_2^T E_2=1>0 \text{ and } F^T(t)F(t)\le\alpha^2 I.$$

Solving the Riccati equation (28) gives the robust controller gain for the generator as

$$\begin{bmatrix}k_1 & k_2 & k_3\end{bmatrix}=\begin{bmatrix}-22.36 & -12.8 & 82.45\end{bmatrix}$$

Thus the robust control law (31) becomes

$$v_f(t)=22.36(\delta(t)-\delta_0)+12.8\omega(t)-82.45(P_e(t)-P_m).$$

The DFL compensating law is given in (29) for the generator excitation.

The responses of the power angle δ(t) at the fault locations (λ=0.4 and λ=0.39) with excitation controller but without TCPS controller (plots 1 and 2 respectively) are shown in Fig. 3. Plot 1 illustrates that the system is stable at the fault location of λ=0.4 with the excitation controller only while the plot 2 illustrates that the system will become unstable at the fault location of λ=0.39. This is because the physical limit of the excitation voltage has been considered.

Fig. 4 shows the responses of the power angle δ(t) at the fault locations λ=0.39 (plot 3), λ=0.07 (plot 4) and λ=0.06 (plot 5) with the excitation and TCPS controller (phase angle control only). Plot 3 illustrates that the system becomes stable at the same fault location (λ=0.39) when the TCPS controller (controlling phase angle only) is used in coordination with the excitation controller. The reason for this is that when the power angle δ(t) increases, the phase shift angle ϕ(t) decreases (Fig. 6). As a result, the effective angle (δ(t)+ϕ(t)) tends to remain constant. Plot 4 illustrates that the system remains stable even when the fault occurs closer to the generator bus (at the fault location λ=0.07). Plot 5 illustrates that the system will become unstable at the fault location of λ=0.06. It is evident from these results that when the fault occurs very close to the generator terminal, the system using the coordinated excitation and TCPS controller (controlling phase angle only) cannot maintain the synchronism.

Fig. 5 shows the responses of the power angle δ(t) at the fault locations λ=0.06 (plot 6) and λ=0.01 (plot 7) with the proposed excitation and TCPS controller (controlling both the phase angle and the magnitude of the injected voltage). Plot 6 illustrates that the system becomes stable at the same fault location (λ=0.06) when the proposed coordinated excitation and TCPS controller (controlling both the phase angle and the magnitude of the injected voltage) is used. Plot 7 illustrates that the system remains stable even when the fault occurs much closer to the generator bus (at the fault location λ=0.01). Thus, by using the proposed nonlinear controller, the transient stability enhancement can be achieved. The capability of the TCPS for the stability enhancement has been demonstrated by computer simulation.

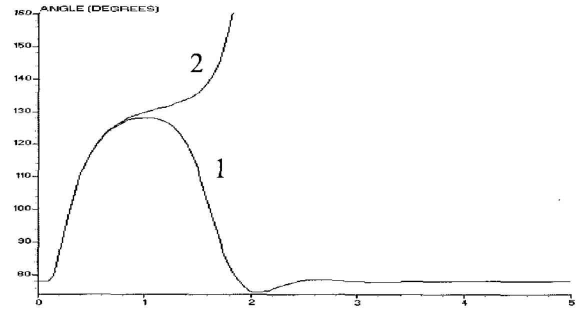

Fig. 3. Responses of δ(t) at λ=0.4 (plot 1) and λ=0.39 (plot 2) with excitation controller only.

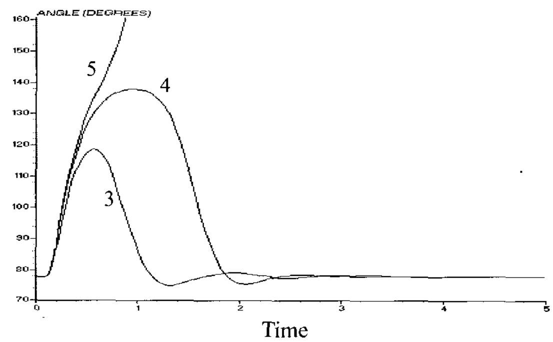

Fig. 4. Responses of δ(t) at λ=0.39 (plot 3), λ=0.07 (plot 4) and λ=0.06 (plot 5) with the excitation and TCPS controller (controlling phase angle only).

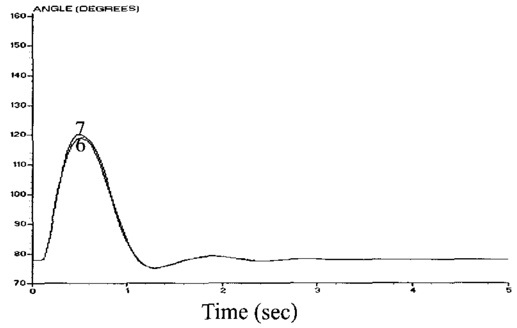

Fig. 5. Responses of δ(t) at λ=0.06 (plot 6) and λ=0.01 (plot 7) with the proposed excitation and TCPS controller (controlling both the phase angle and the magnitude of the injected voltage).

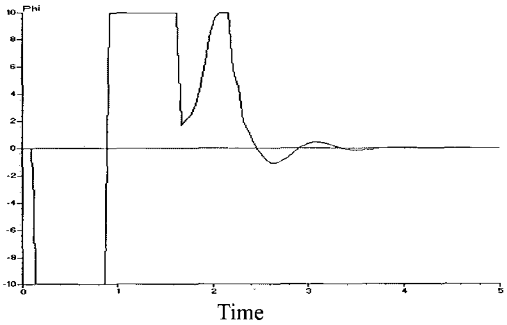

Fig. 6. Response of ϕ(t) at λ=0.01 with the proposed excitation and TCPS controller.

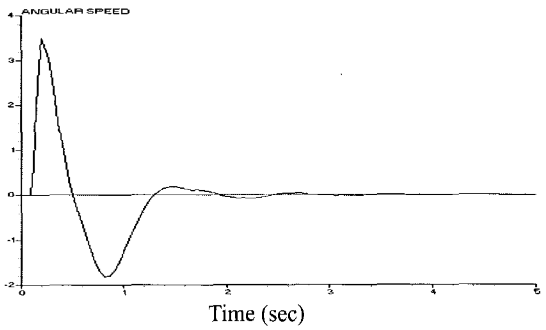

Fig. 7. Response of ω(t) at λ=0.01 with the proposed excitation and TCPS controller.

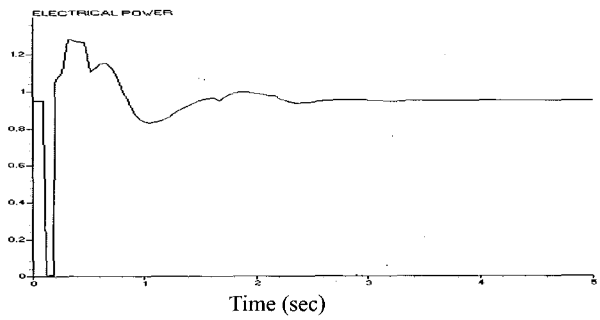

Fig. 8. Response of $P_e(t)$ at λ=0.01 with the proposed excitation and TCPS controller.

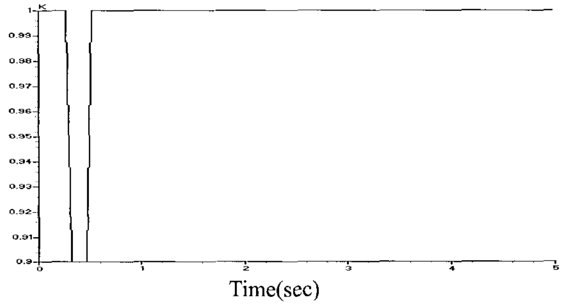

Fig. 9. Response of k(t) at λ=0. 01 with the proposed excitation and TCPS controller.

The responses of the relative speed of the generator ω(t), the real power of the generator $P_e(t)$ and the magnitude of the injected voltage k(t) at the fault location λ=0.01 when the proposed excitation and TCPS controller is used are shown in Figs. 7, 8 and 9 respectively.

6. CONCLUSION

This paper presents a new approach to TCPS control. The research work presents the development of a nonlinear coordinated generator excitation and TCPS controller design. The proposed controller consists of three sub-controllers; one for the generator excitation voltage and the other two for the TCPS. The goal of the coordinated controller design is to allow the sub-controllers to cooperatively improve the transient performance of the power system. The sub-controllers are designed separately based on local measurements only and the design of the proposed coordinated controller is independent of the operating point and fault location.

Digital simulation results presented show that the proposed controller can ensure the transient stability of the power system under a large sudden fault even in a case where a fault occurs near the generator bus terminal.

The proposed controller can be extended for the multimachine system transient stability enhancement. However, further investigations are needed.

APPENDIX: LIST OF SYMBOLS

$\Delta\delta(t)=\delta(t)-\delta_0$; δ(t) : the power angle of the generator (controlled output); δ_0 : the power angle of the generator at the operating point; ω(t) : the relative speed of the rotor of the generator, in rad/sec; P_m : the mechanical input power, in p.u., which is constant; P_e (t) : the active electrical power delivered by the generator, in p.u; ω0 : the synchronous machine speed in rad/sec; $\omega_0 = 2\pi f_0$; D : the per unit damping constant; H : the per unit inertia constant, in seconds; $E_q^{'}(t)$: the transient EMF in the quadrature axis of the generator, in p.u.; $E_q(t)$: the EMF in the quadrature axis of the generator, in p.u.; $E_f(t)$: the equivalent EMF in the excitation coil of the generator, in p.u.; T'_{d0} : the direct axis transient short circuit time constant of the excitation circuit without the armature reaction, in second; $Q_e(t)$: the reactive power, in p.u.; $I_f(t)$: the excitation current, in p.u.; $I_q(t)$: the quadrature axis current, in p.u.; k_c : the gain of the excitation amplifier; $u_f(t)$: the control input of the SCR excitation amplifier of the generator, in p.u. (with gain kc); Y'_{12} : the transient admittance between buses 1 &2; x_{ad} : the mutual reactance between the excitation coil and the stator coil; V_s : the infinite bus voltage (constant); Y'_{11} : transient self-admittance of bus 1; x_d : the direct axis reactance of the generator; x'_d : the direct axis transient reactance of the generator; v_f : external command signal; I_d : direct axis current, in p.u.; x_{ps} : TCPS reactance; $\phi(t)$: the phase shift angle of the TCPS; ϕ_0 : the phase shift angle of the TCPS at the operating point; $\mu_p(t)$: the input to the control system of the TCPS; k_p : the gain of the control system of the TCPS; T_p : the time constant of the control system of the TCPS; k(t) : transformation coefficient of voltage magnitude of TCPS; T_k : the time constant of the control system of the TCPS; k_0 : the transformation coefficient of voltage magnitude of TCPS at the operating point; k_k : the gain of the control system of the TCPS; $u_k(t)$: the input to the control system of the TCPS; λ : the fraction of the faulted line to the left of the fault; $\omega_L(t)$: the relative frequency at the TCPS bus; $\mathbf{Y_{aa}}$ & $\mathbf{Y_{bb}}$: Self-admittances of buses a & b respectively with the TCPS installed; $\mathbf{Y_{ab}}$: Admittance between buses a & b with the TCPS installed; $\mathbf{Y_{ba}}$: Admittance between buses b & a with the TCPS installed; $\mathbf{Y'_{aa}}$ & $\mathbf{Y'_{bb}}$: Self-admittances of buses a & b respectively excluding the admittance of line a-b; $\mathbf{Y_K}$: matrix composed of self- and mutual admittances identified with nodes to be eliminated (in our case nodes a & b between which TCPS is installed); $\mathbf{Y_M}$: matrix composed of self- and mutual admittances identified only with nodes to be retained (in our case *n* number of generator nodes); $\mathbf{Y_L}$: matrix composed of only those mutual admittances common to a node to be retained and to one to be eliminated; $\mathbf{Y_{LT}}$: Transpose of $\mathbf{Y_L}$

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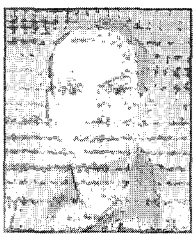

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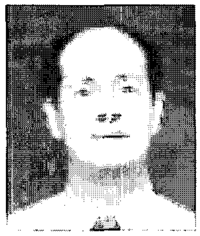

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