Australian Journal of Basic and Applied Sciences, 9(16) Special 2015, Pages: 289-293

ISSN:1991-8178

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

Coordinated Design of PSS and Sliding Mode Based TCSC Controller for Enhancing Dynamic Stability of Power System

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ARTICLE INFO

Article history:
Received 20 January 2015
Accepted 02 April 2015
Published 20 May 2015

Keywords:
Dynamic stability
Power System Stabilizer
Thyristor controlled series compensator
Sliding mode control

ABSTRACT

Coordination control of power system stabilizer (PSS) and Thyristor controlled series compensator (TCSC) gives a new and efficient design for the enhancing power system stability. PSS mainly improves the voltage regulation of the generatorand also enhance the dynamic performance of the power system. HoweverTCSC mainly vary the reactance of the transmission line and improves the stability limit of the power system. TCSC is also known as series compensator and has very fast response.In this paper Sliding mode control (SMC) based system is employed for the control of PSS and TCSC to improve the dynamic stability of a single machine infinite bus (SMIB) power system. System is tested in time domain MATLAB programming and the results show that the proposed scheme with Sliding mode control based system not only attenuate external disturbances on the system, but also power system dynamic performance improves. The results are compared with three different control schemes and also show that more quick response by the proposed method.

To Cite This Article: Akshay Kumar, P.C. Panda, S.C. Swain., Coordinated Design of PSS and Sliding Mode Based TCSC Controller for Enhancing Dynamic Stability of Power System. ***Aust. J. Basic & Appl. Sci.,*** *9(16): 289-293, 2015*

INTRODUCTION

A power system should be operate under all condition from no load to overloading to short circuit and the power system is desired to maintained power quality under all condition. It is desirable to maintain the constancy of voltage magnitude and frequency of power system. Hence the power system stability should be maintain under economical reasons.

To improve the voltage regulation of generator and damp the power system oscillation one of the technique employed is the power system stabilizer (PSS) (Kundur, 1994; Rajendraprasad*et al*., 2011, 2012). The power system stabilizer enhance the dynamic performance of the system using auxillary stabilizing signals to improve the voltage regulation of the generator. Input signals to the PSS are terminal frequency, shaft speed and power. However, in some cases only use of PSS is not effective for long distance power transmission system.Flexible AC transmission system (FACTS) which are effective for improving damping inter-area oscillations, transmission capacity and power system stability. Thyristor controlled series compensator (TCSC) (Hingorani and Gyugi, 2011;Abido, 2009; Swain *et al*., 2010,2014,2015) is the most common FACTS device. TCSC (Mathur and Varma, 2002) provides smooth, rapid and continuous adjustment of the transmission lineimpedance. It also increases the stability margin of the system and very effective in power oscillation.The sliding mode control (SMC) (Juergen and Vadim, 1998; Dash and

Sahoo, 1993, 1996) methods are robust withimpedance. It also increases the stability margin of the system and very effective in power oscillation.The sliding mode control (SMC) (Juergen and Vadim, 1998; Dash and Sahoo, 1993, 1996) methods are robust with respect to perturbations and are developed to design such that it has desired dynamic behavior. It exhibits the desired dynamics performance and insensitivity to unknown perturbations after some interval of time, while the system with a dynamic controller has the same properties starting from any initial state.

This paper presents a single machine infinite bus (SMIB) power system can improve dynamic stability with TCSC, PSS and sliding mode based controller. This paper are summarized as follows: Section II, gives a modelling of different power system component (synchronous generator, PSS and TCSC)

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to understand its considered structure. In section III, control system (SMC) designed is described. In section IV, simulation results are presented.

1. System Modelling:

1-1. Synchronous Generator Modelling:

A single machine infinite bus (SMIB) power system is shown in fig 1 for analysis:

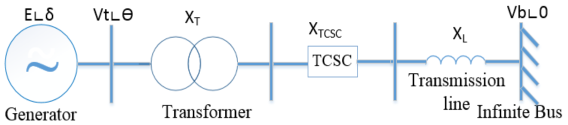


Fig. 1: Single machine infinite bus.

The SMIB power system employed with PSS and TCSC are installed at the generator terminal. The synchronous generator is adopted with third order model (Kundur, 1994). The generator dynamic equation can be written as follow:

$$\dot{\delta} = w - w_o \quad (1)$$

$$\dot{w} = -\frac{D}{2H}[\mathrm{w - w_0}] + \frac{\mathrm{w_0}}{2H}[Pm - Pe] \quad (2)$$

$$\dot{E_q'} = \frac{1}{Td0}[Ef - (Xd - Xdd)Iq - Eq] \quad (3)$$

$$P_e = V_d I_d + V_q I_q \quad (4)$$

$$V_t^2 = V_d^2 + V_q^2 \quad (5)$$

$$V_d = X_q I_q \quad (6)$$

$$V_q = E_q - X_d I_d \quad (7)$$

1-2. Exciter system modeling:

The excitation of the alternator is regulated by varying the main exciter voltage and this can be used to improve the voltage regulation of the generator. Excitation system with a PSS (Wang *et al.*, 2001) is shown in fig 2.

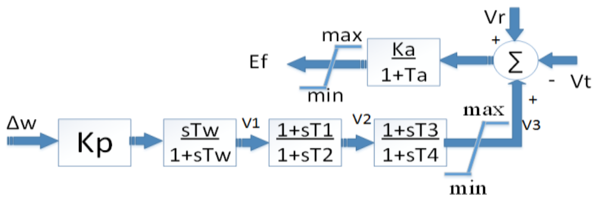


Fig. 2: Excitation system with a PSS.

The dynamic equations are given below:

$$\dot{v}1 = Kp\Delta\dot{w} - \frac{1}{Tw}\,v1 \quad (8)$$

$$\dot{v}2 = \frac{1}{T2}[T1\dot{v}1 + v1 - \Delta v2] \quad (9)$$

$$\dot{v}3 = \frac{1}{T4}[T3\dot{v}2 + v2 - v3] \quad (10)$$

$$\dot{E}f = \frac{1}{Ta}[Ka[Vr - Vt + v3] - Ef] \quad (11)$$

The gain constant Kp determine how much amount of damping introduced by power system stabilizer (PSS). The value of time constant Tw in the ranges from 1 – 20 sec and act as a high pass filter. Time constants (T1, T2, T3 and T4) gives amount of phase lead lag compensation between the input and the output signals.

1-3. TCSC controller modeling:

TCSC is shown in fig 3 is based on the conventional lead-lag structure controller. The input signal of TCSC is speed deviation of the generator and the output signal of TCSC is the reactance offered by TCSC (Sidhartha, 2009). TCSC consists of three blocks (a) gain block with gain constant K_T, (b) washout block with time constant T_T and (c) lead lag phase compensation block (time constants T^1, T^2, T^3 and T^4). The washout block with time constant T_T should be chosen such that it act as a high pass filter. The phase compensation block (lead-lag block) serves as necessary phase compensation between the input and the output signals.

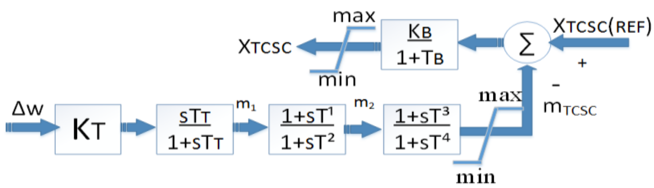


Fig. 3: TCSC based controller.

TCSC dynamic equation can be written as follow(Li *et al.*, 2000; Srivastav*et al.*, 1999; Zhao and Jiang, 1998; Alberto, 2003)

$$\Delta\dot{m}1 = K_T\Delta\dot{w} - \frac{1}{T^1}\Delta\mathrm{m}1 \quad (12)$$

$$\Delta\dot{m}2 = \frac{1}{T^2}[\mathrm{T}^1\Delta\dot{m}1 + \Delta\mathrm{m}1 - \Delta\mathrm{m}2] \quad (13)$$

$$\Delta\dot{m}\mathrm{TCSC} = \frac{1}{T^4}[\mathrm{T}^3\Delta\dot{m}2 + \Delta\mathrm{m}2 - \Delta\mathrm{mTCSC}] \quad (14)$$

$$\dot{\mathrm{X}}_{TCSC} = \frac{1}{TB}[K_B(X_{\mathrm{TCSCref}} - \mathrm{mTCSC}) - X_{\mathrm{TCSC}} \quad (15)$$

1-4 Linearized power system modeling:

The non-linear dynamic equation can be linearized as given below (Pourbeikand Gibbard, 1998; Panda and padhy, 2007).

$$\dot{\delta} = \Delta w_o \quad (16)$$

$$\Delta\dot{w} = \frac{w_\circ}{2H}[-\Delta Pe - D\frac{\Delta w}{w_\circ}] \quad (17)$$

$$\Delta\dot{E}'q = \frac{1}{Td0}[-\Delta Ef - (Xd - Xdd)\Delta Id - \Delta E'q] \quad (18)$$

$$\Delta\dot{E}f = \frac{1}{Ta}[\mathrm{Ka}\ (-\Delta\mathrm{Vt} + \Delta\mathrm{V3}) - \Delta\mathrm{Ef}] \quad (19)$$

$$\Delta\dot{X} = \frac{1}{Tt}[Kt(\Delta m\mathrm{TCSC}) - \Delta X_{TCSC}] \quad (20)$$

$$\Delta\dot{v}1 = k_{st}\Delta\dot{w} - \frac{1}{Tw}\Delta v1 \quad (21)$$

$$\Delta\dot{v}2 = \frac{1}{T2}[\mathrm{T1}\Delta\dot{v}1 + \Delta v1 - \Delta v2] \quad (22)$$

$$\Delta\dot{v}3 = \frac{1}{T4}[\mathrm{T3}\Delta\dot{v}2 + \Delta v2 - \Delta\mathrm{v}3] \quad (23)$$

$$\Delta\dot{m}1 = \mathrm{Kt}\Delta\dot{w} - \frac{1}{T^1}\Delta\mathrm{m}1 \quad (24)$$

$$\Delta\dot{m}2 = \frac{1}{T^2}[\mathrm{T}^1\Delta\dot{m}1 + \Delta\mathrm{m}1 - \Delta\mathrm{m}2] \quad (25)$$

$$\Delta\dot{m}\mathrm{TCSC} = \frac{1}{T^4}[\mathrm{T}^3\Delta\dot{m}2 + \Delta\mathrm{m}2 - \Delta\mathrm{mTCSC}] \quad (26)$$

$$\Delta\dot{X}_{TCSC} = \frac{1}{TB}[K_B(X_{\mathrm{TCSCref}} - \mathrm{mTCSC}) - X_{\mathrm{TCSC}}]$$

(27)

2. Control System Design:

A Variable structure control (Vadim, 1977) model is designed for a single machine connected to infinite bus power system. Synchronous machine is third order linearized system model. The control is designed such that the state of the controlled system on the switching surface. State trajectory is define by equation of the surface only when state is constrained to the surface. The stabilizer performance is evaluated on a non-linear system model under different disturbance conditions. The nonlinear state equation of power system is given as

$\dot{X} = \mathrm{Ax} + \mathrm{Bu}$

Where, $\mathrm{x} = [\Delta\delta\ \Delta\mathrm{w}\ \Delta\mathrm{E'q}\ \Delta\mathrm{Efd}\Delta X_{TCSC}]^T$ .The parameter of A and B are as follows:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -25.443 & 0 & -45.9478 & 0 & -19.1225 \\ -.1157 & 0 & -.2125 & -.1982 & -.0824 \\ -593.9 & 0 & -151.9 & -1000 & -502.9 \\ -503.9 & 0 & -51.9 & 0 & -1000 \end{bmatrix}$$

$\mathrm{B} = [0\ 0\ 0\ 0\ 100]^T$ and u is the stabilising signal. The value of matrix A can be obtained from Appendix I.The switching hyperplane for the sliding mode control is designed using the following equation:

$\mu = C_1\Delta\delta + C_2\Delta\mathrm{w} + C_3\Delta\mathrm{E'q} + C_4\Delta\mathrm{Efd} + \Delta X_{TCSC}$

Where C_1, C_2, C_3, and$C_4$are to be determined. These value should be chosen properly so that it will give best dynamic performance. The necessary condition for the sliding mode control on the switching surface $\mu = 0$, is

$\mu\dot{\mu} < 0$, Where, $\dot{\mu}$ is the time derivative of μ.Equating μ=0 and find the value of eigen values using matrix A, we can get the value of hyperplane coefficient C_1, C_2, C_3 and C_4. The expression for the control signal Δu is written as $\Delta\mathrm{u} = \mathrm{A1}\Delta\delta + \mathrm{A2}\Delta\mathrm{w} + \mathrm{f1\ Sgn}(\mu)$Where,

$$A_1 = \begin{cases} \boldsymbol{\alpha}_1 & \text{if } \mu\,\Delta\delta > 0 \\ \boldsymbol{\beta}_1 & \text{if } \mu\,\Delta\delta < 0 \end{cases}$$

$$A_2 = \begin{cases} \boldsymbol{\alpha}_2 & \text{if } \mu\Delta w > 0 \\ \boldsymbol{\beta}_2 & \text{if } \mu\Delta w < 0 \end{cases}$$

$$\mathrm{Sgn}(\mu) = \begin{cases} 1 & \mu > 0 \\ -1 & \mu < 0 \\ 0 & \mu = 0 \end{cases}$$

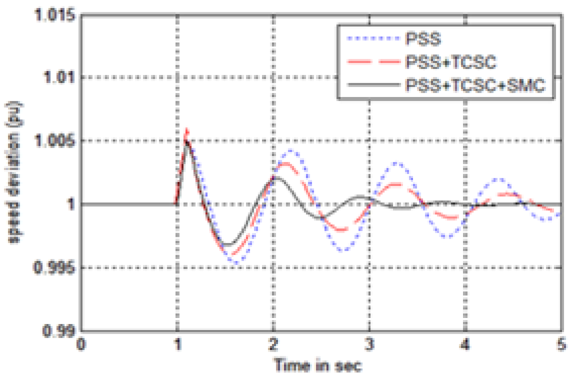
and $\mathrm{f1} > |\, a\ \Delta E\mathrm{fd}\,|$. The feedback gains A_1 , A_2 are chosen to satisfy $\mu\dot{\mu} < 0$. $\boldsymbol{\alpha}_1$,$\boldsymbol{\beta}_1$, $\boldsymbol{\alpha}_2$, $\boldsymbol{\beta}_2$ and a should be selected by the designer to provide stability and damping to the system.

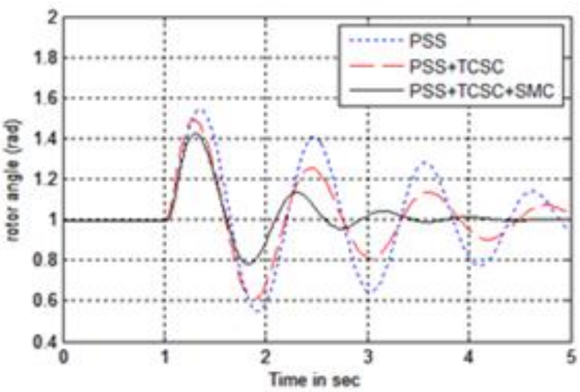
3. Simulation Result:

This section illustrates the simulation of the mathematical model containing a single generator equipped with the power system stabilizer (PSS) and connected to an infinite bus. A Thyristor controlled series compensator (TCSC) and Power System Stabilizers (PSS) are used to improve dynamic stability and the power system oscillation damping (Lei *et al*., 2001). The system of two controller are coordinate by variable sliding mode controller. Two control schemes are analyzed to get dynamic performance of the coordinate controller. The test system is analyzed with only PSS, with PSS+TCSC, and with PSS+TCSC+SMC. Two different condition are analyzed to get dynamic performance of the test system: (1) Three phase fault at terminal of the generator. (2) Changing the input of the turbine.

3-1. Three phase fault occur at terminal of the generator:

A three phase fault is applied at generator terminal of single machine infinite bus power system. Simulation is done using MATLAB programing model. Here three phase short circuit fault for a period of five cycle applied at 1 sec and cleared at 1.1 sec. After the fault original system is restored. The simulation results are shown in figs. 4.





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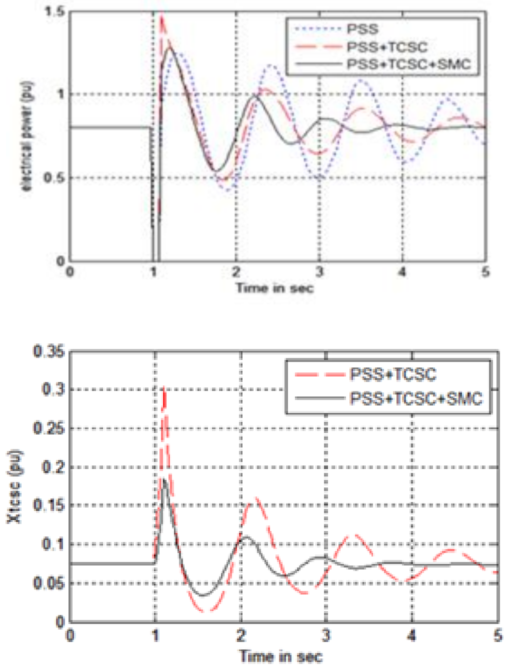
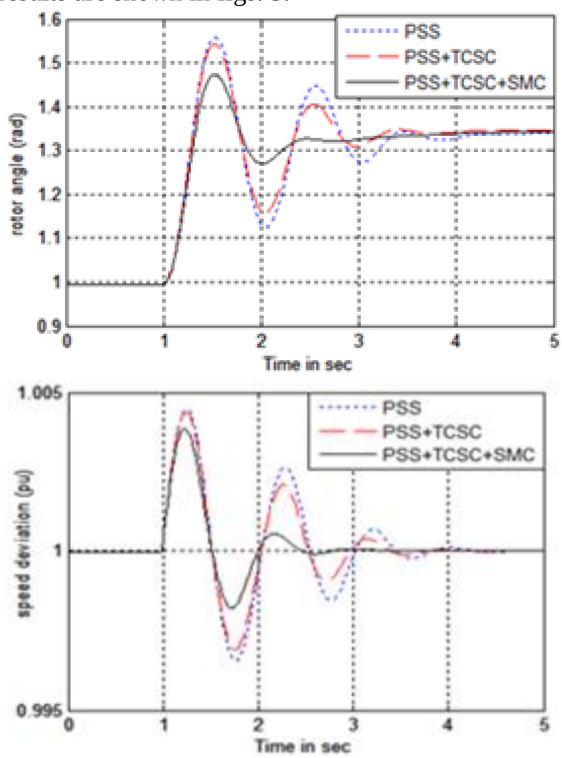


Fig. 4: System dynamic response: rotor speed variation (pu), rotor angle (rad), electrical power variation (pu), reactance offered by TCSC (pu).

3-2. Changing input of the turbine:

A 50% step change in the mechanical power input at the moment t=1 sec. The mechanical power reference is increased by 50% over the original value, i.e. Pm = 0.8 to Pm=1.2. The simulation results are shown in figs. 5.



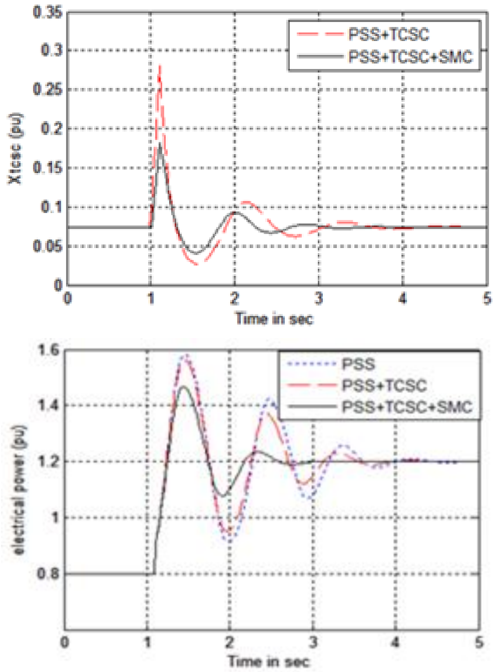


Fig. 5: System dynamic response: rotor angle (rad), rotor speed variation (pu), reactance offered by TCSC (pu), electrical power variation (pu).

4. Conclusion:

A non- linear system is tested in time domain MATLAB model. A single machine infinite-bus (SMIB) power system presented in this paper provides stability analysis of power system and generator dynamic behavior. In this paper, sliding mode control is a relatively new way of dynamic stability improvement for Power System Stabilizer (PSS) and TCSC is discussed. Simulation results show clearly improvement of the system using the Slide mode control controller improves the stability performance of the power system. It also damped out the power system oscillation.

Appendix – I:

$$\begin{pmatrix} \Delta\dot{\delta} \\ \Delta\dot{w} \\ \Delta\dot{E}_q' \\ \Delta\dot{E}_{fd} \\ \Delta\dot{X}_{TCSC} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ -\frac{Wo}{2H}f_1 & -\frac{D}{2H} & -\frac{Wo}{2H}f_3 & 0 & -\frac{Wo}{2H}f_5 \\ -\frac{(Xd-Xdd)}{Td0}a_1 & 0 & -\frac{(Xd-Xdd)}{Td0}a_3 & -\frac{1}{Td0} & -\frac{(Xd-Xdd)}{Td0}a_5 \\ -\frac{Ka}{Ta}e_1 & 0 & -\frac{Ka}{Ta}e_3 & -\frac{1}{Ta} & -\frac{Ka}{Ta}e_5 \\ -\frac{Kz}{Tz}e_1 & 0 & -\frac{Kz}{Tz}e_3 & 0 & -\frac{1}{Tz} \end{pmatrix}$$

Where,

$X_{TCL} = X_T - X_{TCSC} + X_L$; $X_{DT} = X_{dd} + X_{TCL}$; $X_{QT} = X_q + X_{TCL}$; $I_d = \frac{1}{X_{DT}}$ E'q $-\frac{1}{X_{DT}}$ Vb cosδ; $I_q = \frac{1}{X_{QT}}$ Vb sinδ; a1 $= \frac{1}{X_{DT}}$ Vb sinδ; a3 $= \frac{1}{X_{DT}}$; a5 $= -\frac{Vb\cos\delta - Eq'}{(X_{DT})^2}$;b1 $= \frac{1}{X_{QT}}$ Vb cosδ;

$b5 = \frac{Vb\ sin\delta}{(X_{QT})^2}$; Ci = Xqbi, $i = 1,5$; $d_i = -X_{dd}a_i$, $i = 1,5$; $d_3 = 1 - X_{dd}a_3$; $e_3 = [V_{tq}d_3]/V_t$
$e_i = [V_{td}C_i + V_{tq}d_i]/V_t$, $i = 1,5$; $f_i = V_{td}a_i + I_dC_i + V_{tq}b_i + I_qd_i i = 1,5$;
$f_3 = V_{td}a_3 + I_qd_3$

Appendix – II:

System parameter: All data are specified in pu:
Generator parameter:
X_d= 0.81, X_{dd}= 0.3, X_q= 0.6, X_T = 0.1, X_L=.15, H = 4, V_t = 1, V_b = 1, f = 50 Hz, D = 0,T_{d0} = 5.04, P_m = 0.8
Initial condition:
$X_{TCSCref}$= 0.0674 , δ_0 = .951 (radian)

Nomenclature:

w Relative speed of the generator in rad/s
δ Rotor angle of the generator in radians
w_o Synchronous speed of the generator in rad/s
H Inertia constant
D Damping constant
V_t Generator terminal voltage in p.u.
P_m Mechanical input power in p.u.
Pe Active power delivered by the generator in p.u.
T_{d0} Time constant of the excitation winding in sec
X_d Direct axis reactance of the generator in p.u.
X_{dd}Direct axis transient reactance of the generator in pu
X_q q-axis synchronous reactance in p.u.
X_T Reactance of the transformer in p.u.
X_L Line impedance in p.u.
X_{TCSC} TCSC reactance in p.u.
Ef Excitation voltage in p.u.
E'_q q-axis transient voltage in p.u.
V_b Infinite bus voltage in p.u
I_d d – axis component of current
I_q q – axis component of current

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