Stability Analysis of Single Machine Infinite Bus Power System Employing Robust Fuzzy Logic TCSC Controller

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***Abstract*— This proposed research work focuses on the analytical design of robust fuzzy logic Thyristor Controlled Series Compensator (TCSC) for enhancing the dynamic stability of a Single Machine Infinite Bus (SMIB) power system. The performance of the proposed system with robust fuzzy logic based TCSC is tested with the system having conventional TCSC controller and robust H_∞ TCSC controller. These controller actions are more effective in damping the low frequency oscillations resulting from various small disturbances like mechanical power input, terminal voltage setting, and speed deviation. Under these various disturbances condition, the stability analysis of the proposed system is also carried out. Moreover, comparisons of Lead-lag TCSC, robust H_∞ TCSC and robust fuzzy logic TCSC controllers based on settling time are analyzed. Further, the obtained results show that the system with robust fuzzy logic controller is capable of stabilizing the system faster than the conventional and H_∞ TCSC controllers.**

Keywords— **Power system stability, robust control, fuzzy logic, SMIB power system, Thyristor Controlled Series Compensator**.

1. Introduction

Modern power systems are characterized by extensive system interconnections and increasing dependence on control for optimal utilization of existing resources. The supply of reliable and economic electrical energy is a major determinant of industrial progress and consequent rise in the standard of living. The increasing demand for electric power coupled with resource and environmental constraints pose several challenges to system planners. The generation may have to be sited at location far away from load centers [1]. However, con-impetus to seek technological solutions for exploiting the high thermal loading limits of EHV lines. With deregulation of power supply utilities, there is a tendency to view the power networks as highways for transmitting electric power from wherever it is available to place where required, depending on the pricing that varies with time of the day. Stability of power systems continue to be of major concern in system operation. This arises from the facts that in steady state, the average electrical speed of all the generators must remain the same anywhere in the system. This termed as the synchronous operation of a system. Any disturbance small or large can affect the synchronous operation. For example, there can be a sudden increase in the load or loss of generation. Another type of disturbance is the switching out of a transmission line, which may occur due to overloading or a fault. Due to this the stability of the system is affected. Then the system can settle to a new original steady state after the transients disappear.

By means of flexible and rapid control over the AC transmission parameters and network topology, Flexible Ac Transmission System (FACTS) technology can facilitate the power control, enhance the power control, enhance the power transfer capability, decrease the line losses and generation costs, and improve the stability and security of the power system [2]. For the analysis of small signal stability accurate representation of system dynamics along with tuned FACTS controller is essential.

Conventional TCSC is used in existing power system stabilizers is contribution in enhancing power system dynamic stability. The parameters of TCSC are determined based on linearized model of the power system around a nominal operating point where they can provide good performance. Since power systems are highly nonlinear systems, with configurations and parameters that change with time, the TCSC design based on the linearized model of the power system cannot guarantee its performance in a practical operating environment. To improve the performance of conventional TCSC, numerous techniques have been proposed for their design, such us using genetic algorithm, neural networks, fuzzy logic and many other nonlinear control techniques.

This flow of this research paper is organized as described below. In Section 2 describes with design of conventional TCSC controller and robust TCSC controller. In section 3 focuses how the modeling, simulation and performance of SMIB power system is analyzed. In section 4 proposes a designing of robust fuzzy logic TCSC controller with the system. In section 5, the analysis of SMIB with fuzzy robust TCSC controller and comparisons with the conventional controllers is obtained. The section 6 concludes the stability analysis of SMIB system using robust fuzzy logic TCSC controller.

2. Design of conventional TCSC controller

Thyristor Controlled Series Compensation is used in power systems to dynamically control the reactance of a transmission line in order to provide sufficient load compensation. The benefits of TCSC are seen in its ability to control the amount of compensation of a transmission line, and in its ability to operate in different modes. These traits are very desirable since loads are constantly changing and cannot always be predicted [3].

The circuit diagram of a TCSC is shown in Fig.1. It consists of three components: capacitor banks C, bypass inductor L and bidirectional thyristors SCR_1, SCR_2. In Figure 1, i_C and i_L are the instantaneous values of the currents in the capacitor banks and inductor, respectively. Here i_S the instantaneous current of the controlled transmission line and v is the instantaneous voltage across the TCSC.

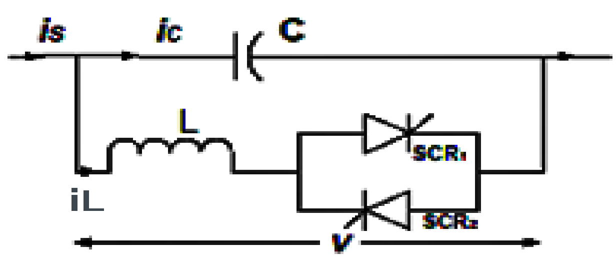

Fig.1: Variable inductor connected in shunt with a fixed capacitor

The control of the TCSC is achieved by the firing angle signal α, which changes the fundamental frequency reactance of the compensator. There exists a steady-state relationship between the firing angle α and the reactance X_{TCSC} (α). This relationship can be described in the following equation.

$$X_{TCSC}(\alpha) = X_C - \frac{X^2{}_C}{X_C - X_P}\frac{\sigma + \sin\sigma}{\Pi} + \frac{4X^2{}_C}{X_C - X_P} \frac{\cos^2(\sigma/2)(k\tan(k\sigma/2) - \tan(\sigma/2))}{(k^2-1)\Pi} \quad (1)$$

Where

X_C = Nominal reactance of the fixed capacitor C

X_P = Inductive reactance of inductor L connected parallel with C

σ = *2*(π −α) = Conduction angle of TCSC controller

k = Compensation ratio.

The equation (1) is the fundamental frequency reactance offered by TCSC, $X_{TCSC}(\alpha)$ is a unique-valued function; the TCSC is modeled here as a variable capacitive reactance within the operating region defined by the limits imposed by α. Thus $X_{TCSC_{min}} \leq X_{TCSC}(\alpha) \leq X_{TCSC_{max}}$, with $X_{TCSC\ min} = X_{TCSC}\ (180^0)$ and $X_{TCSCmax} = X_{TCSC}\ (\alpha_{min})$. In this paper, the Controller is assumed to operate only in the capacitive region, i.e., $\alpha_{min} > \alpha_r$ where α_r corresponds to the resonant point, as the inductive region associated with $90^0 < \alpha < \alpha_r$ induces high harmonics that cannot be properly modeled in stability studies [4].

2.1 Robust H∞ Loop shaping TCSC controller

The robust TCSC are designed based on H∞ loop shaping control [5]. The design procedure is divided into 3 steps as follows.

Step 1: Loop shaping

As shown in Fig.2, a pre-compensator W_1 and a post -compensator W_2 are employed to form the augmented plant $G_S = W_2GW_1$, which is enclosed by a solid line.

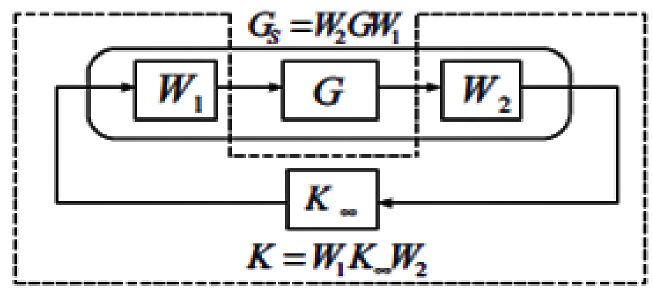

Fig. 2: Shaped plants G and designed robust controller K.

The designed robust stabilizer $K = W_1K_\infty W_2$ is enclosed by a dotted line where K_∞ is the H∞ controller. The weighting function can be selected as W_1 = W and W_2 = 1[6] and [15].

Step 2: Formulation of H∞ robust stabilization problem

A shaped plant Gs is expressed in form of normalized left co-prime factor $G_s = M_s^{-1}N_s$, when the perturbed plant G_Δ is defined as,

$$G_\Delta = \{(M_s + \Delta M_s)^{-1}(N_s + \Delta N_s) : \|[\Delta N_s\ \Delta M_s]\|_\infty \leq 1/\gamma \quad (2)$$

Where, ΔM_s and ΔN_s are stable unknown transfer functions which represent uncertainties in the nominal plant model G. Based on this definition, the H∞ robust stabilization problem can be established by G_Δ and K as depicted in Figure 4. The objective of robust control design is to stabilize not only the nominal plan G but also the family of perturbed plant G_Δ. In equ (2) 1/γ is defined as the robust stability margin [7].

The maximum stability margin in the face of system uncertainties is given by the lowest achievable value of γ, i.e. γ_{min}. Hence, γ_{min} implies the largest size of system uncertainties that can exist without destabilizing the closed loop system in Fig. 4. The value of γ_{min} can be easily calculated from

$$\gamma_{\min} = \sqrt{1+\lambda_{\max}(XZ)} \qquad (3)$$

Where $\boldsymbol{\gamma}_{\max}$ (XZ) denotes the maximum Eigen value of XZ. For minimal state-space realization (A, B, C, D) of s G_s, the values of X and Z are unique positive solutions to the generalized control algebraic Riccati equation [8].

$$(A-BS^{-1}D^{T}C)^{T}X + X(A-BS^{-1}D^{T}C)^{T} - XBS^{-1}B^{T}X + C^{T}R^{-1}C = 0 \qquad (4)$$

And the generalized filtering algebraic Riccati equation,

$$(A-BS^{-1}D^{T}C)Z + Z(A-BS^{-1}D^{T}C)^{T} - ZC^{T}R^{-1}CZ + BS^{-1}B^{T} = 0 \qquad (5)$$

Where $R = I + DD^T$ and $S = I + D^TD$ [14]. Note that no iteration on $\boldsymbol{\gamma}$ is needed to solve for $\boldsymbol{\gamma}_{\min}$. To ensure the robust stability of the nominal plant, the weighting function is selected so that $\gamma_{\min} \le 4.0$ [9]. If $\gamma_{\min}$ is not satisfied, then adjust the weighting function.

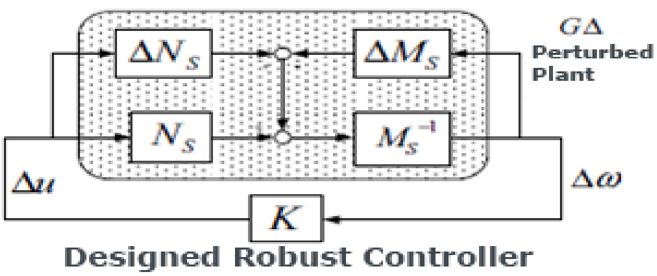

Fig. 3: H_∞ robust TCSC controller.

Step 3: Determination of Robust controller

The K_∞ controller in Figure 3 can be determined by,

$$K\infty = \begin{bmatrix} A+BF+\gamma^{2}(L^{T})^{-1}ZC^{T}(C+DF) & \gamma^{2}(L^{T})^{-1}ZC^{T} \\ B^{T}X & -D^{T} \end{bmatrix} \qquad (6)$$

Where, $F = -S(D^TC + B^TX)$ and $L = (1-\gamma^2)I + XZ$. .

Next, find robust controller $K(s) = W_1K_\infty W_2$ that satisfies the necessary condition.

$$\left\| \begin{matrix} I \\ K\infty \end{matrix} (I - G_S K_\infty)^{-1} [I \;\; G_S] \right\|_\infty \le \gamma \qquad (7)$$

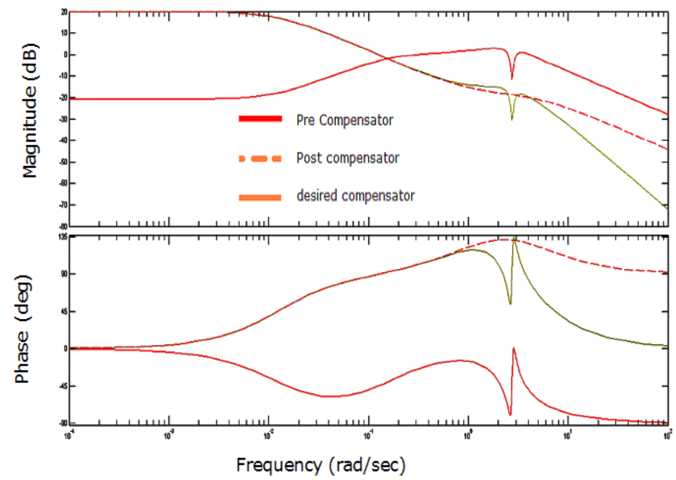

Fig. 4: Bode plot of loop shaping TCSC controller with W_1 and W_2 matrix

Fig.4 depict the bode plot of loop shaping TCSC controller, here the magnitude plot of the robust TCSC controller is between the pre-compensator W_1 and post compensator W_2 this signifies the stabilizing effects of the controller.

3. Analysis of SMIB power system

3.1 System Modelling

The Single-Machine Infinite-Bus (SMIB) power system installed with a TCSC, shown in Fig.5, is considered in this study. In the Fig. 5, X_T and X_L represent the reactance of the transformer and the transmission line respectively. Also V_T and V_B are the generator terminal and infinite bus voltage respectively.

In the design of electromechanical mode damping stabilizer, a linearized incremental model around an operating point is usually employed. The Fig.6 shows the *Phillips-Heffron model* of the power system with FACTS devices is obtained by linearizing nonlinear equations of the power system around an operating condition [11].

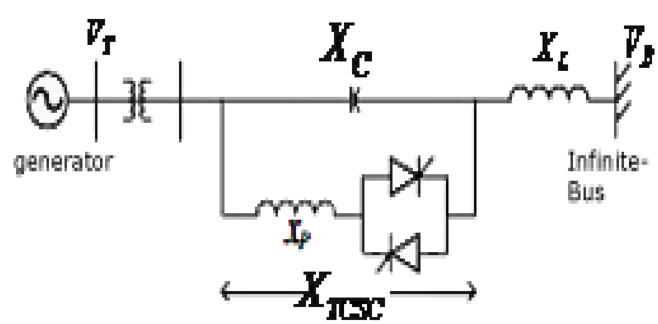

Fig.5: Single Machine Infinite Bus power system with TCSC

3.2 Non linear modeling

In the non linear modeling of SMIB system we use the synchronous generator which is represented by model 1.0, [17] i.e. with field circuit and one equivalent damper winding on q axis. The machine equations of stator and rotor windings are described by [12],

Stator winding equation

$$V_q = -r_s i'_q - x_d i_d + E_q \tag{8}$$

$$V_d = -r_s i'_d + x_q i_q + E_d \tag{9}$$

Where,

r_s - The stator winding resistance

$x_d{}'$ - The d-axis transient resistance

$x_q{}'$ - The q-axis transient resistance

$E_q{}'$ - The q-axis transient voltage

$E_d{}'$ - The d-axis transient voltage

Rotor winding equation

$$T'_{do}\frac{dE'_q}{dt} + E'_q = E_f - (x_d - x'_d)i_d \tag{10}$$

$$T'_{qo}\frac{dE'_d}{dt} + E'_d = (x_q - x'_q)i_d \tag{11}$$

Where,

$T_{do}{}'$ - is the d-axis open circuit transient time constant

$T_{qo}{}'$ - is the q-axis open circuit transient time constant

E_f - is the field voltage

3.3 Linearized modelling

The Linearized model of SMIB system with TCSC controller is represented by *Phillips-Heffron linear model* as shown in Fig. 6 [18].

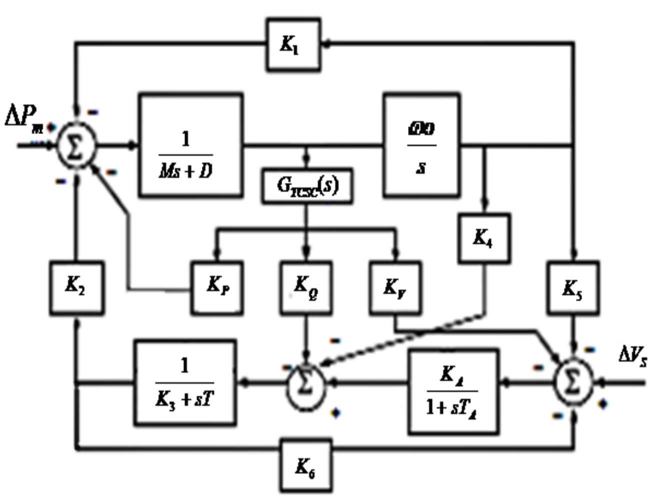

Fig.6: Phillips-Heffron model of SMIB with TCSC

The mathematical model of the Linearized SMIB system is as follows;

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{12}$$

$$\Delta\omega = [-K_1 - \Delta\delta - K_2\Delta E'_q - K_p\Delta\sigma - D\Delta\omega]/M \tag{13}$$

$$\Delta E'_q = \frac{[-K_3\Delta E_q - K_4\Delta\delta - K_q\Delta\sigma + \Delta E_{fd}]}{T'_{do}} \tag{14}$$

$$\Delta E'_{fd} = \frac{[-K_A(K_5\Delta\sigma + K_6\Delta E'_q + K_v\Delta\sigma) - \Delta E_{fd}]}{T'_A} \tag{15}$$

Where,

$$K_1 = \frac{\partial P_6}{\partial\delta} \quad K_2 = \frac{\partial P_6}{\partial E'_q} \quad K_3 = \frac{\partial E_q}{\partial E'_q}$$

$$K_4 = \frac{\partial E_q}{\partial\delta} \quad K_5 = \frac{\partial V_T}{\partial\delta} \quad K_6 = \frac{\partial V_T}{\partial E'_q}$$

4. Design of robust fuzzy logic TCSC controller

The Robust fuzzy logic controller design consists of the following steps:

- Identification of input and output variables
- Construction of control rules
- Establishing fuzzification method and fuzzy membership functions.
- Selection of the compositional rule of inference
- Defuzzification method, so transformation of the fuzzy control statement into specific actions.

The variables for FLTCSC are speed deviation, acceleration and voltage. The speed deviation and acceleration are inputs variables and voltage is the output variables [15], [16]. In practice, only shaft speed is readily available. The acceleration signal can be derived from speed signals measured at two successive sampling using,

$$\Delta\omega(k) = \frac{\Delta\omega(k) - \Delta\omega(k-1)}{\Delta T} \tag{16}$$

Each of the input and output variables are seven linguistic fuzzy: NB (Negative Big), NM (Negative Medium), NS (Negative Small), Ze (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big). The triangular membership functions are used to define the degree of membership. The variables are normalized by multiplying with gains so that their value lies between -1 and 1. The membership functions for inputs are shown in Fig.7& Fig.8 and outputs are shown in Fig.9.

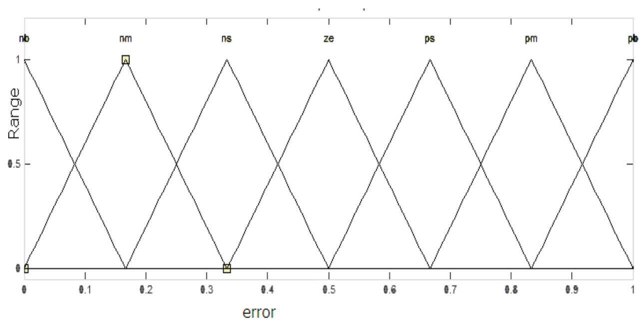

Fig. 7: Error membership function

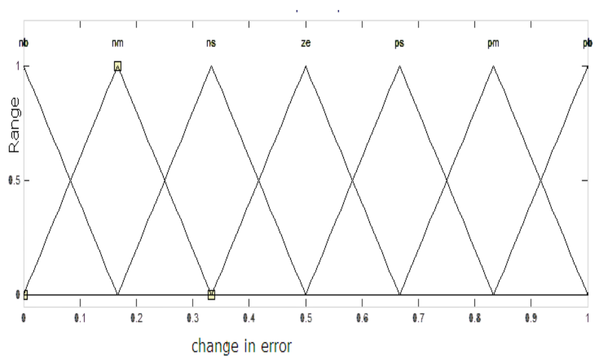

Fig. 8: Change in error membership function

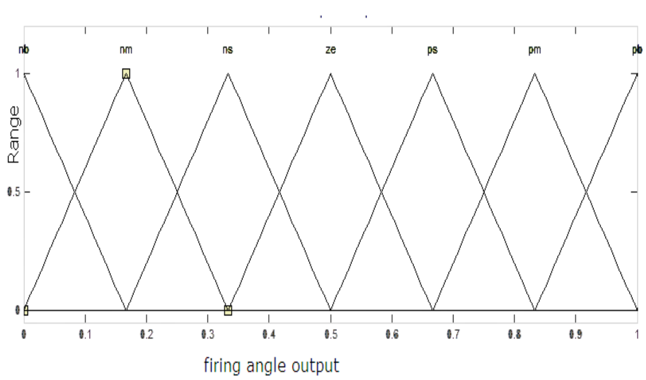

Fig.9: Firing angle membership function.

The two inputs are speed and acceleration, which results in 49 rules for each machine. In case, IF e (t) is PB and derivative of e (t) is zero, THEN the K_P is PB. All the 49 rules are explained in Table-1.The stabilizers output is obtained by applying a particular rule expressed in the form of membership functions. Finally the output membership function of the rule is calculated.

Table-1: Rule base of fuzzy logic controller

	Change in error						
Error	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NM	NS
NM	NB	NM	NM	NM	NS	NS	ZE
NS	NM	NM	NS	NS	ZE	ZE	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	ZE	ZE	PS	PS	PM	PM
PM	NS	PS	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PB	PB	PB	PB

5. Analysis of SMIB with fuzzy robust TCSC controller

The simulink model for simulations of SMIB with fuzzy robust TCSC controller is shown in Fig. 10. The characteristics showing the variation in speed deviation, accelerating power and terminal voltage are presented in Fig. 11. It observes that the oscillations are more pronounced when a system is perturbed with constant field voltage after witch it becomes stable. The excitation system parameters are K_A = 200 and T_A= 0. 02. The time response of the angular speed, angular position for a 5% step change in mechanical input is presented in Fig. 12.

The model used in simulink to analyze the effect of robust fuzzy logic TCSC controller in damping small signal oscillations when implemented on SMIB system is shown in Fig. 10.

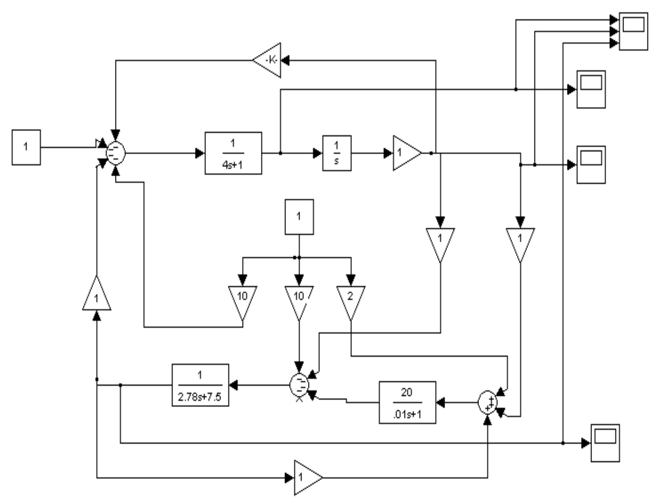

Fig. 10: Simulink model of SMIB with robust fuzzy TCSC controller

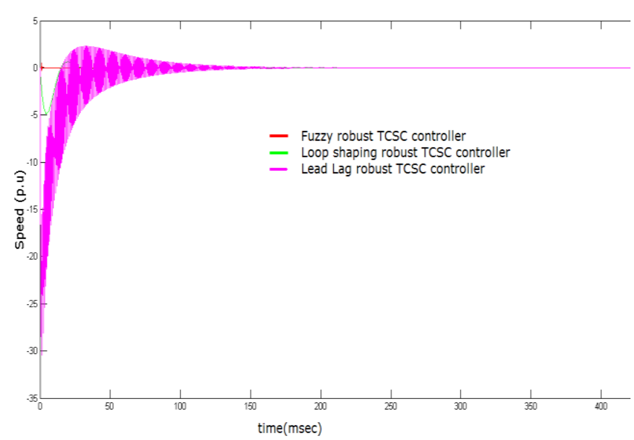

Fig.11: Speed deviation of SMIB with Lead Lag TCSC and robust fuzzy logic TCSC controller.

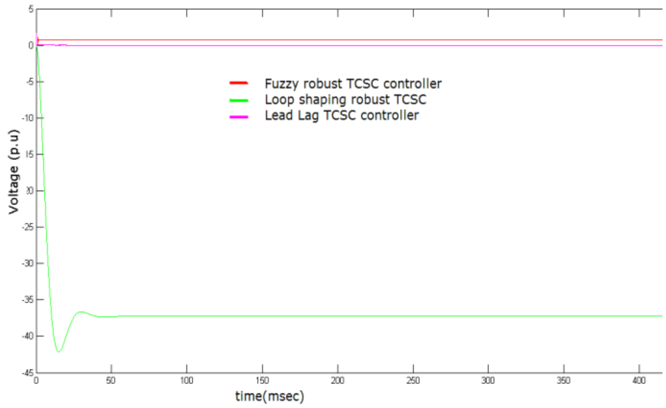

Fig.12: Terminal voltage of SMIB with Lead Lag TCSC and Robust Fuzzy logic TCSC controller.

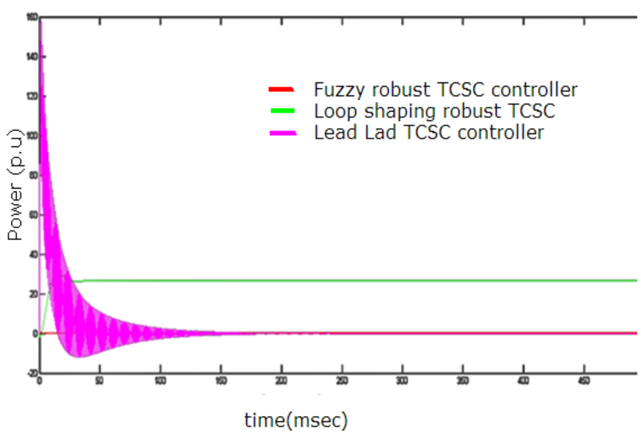

Fig.13: Accelerating power of SMIB system with Lead Lag controller with Robust Fuzzy logic TCSC controller.

To compare the performance of conventional TCSC and robust fuzzy logic based TCSC, the step response are shown in Fig. 11, Fig. 12and Fig. 13. From the above results, it can be perceived that with the application of fuzzy logic robust TCSC controller, rise time and settling time of the system decreases. The system reaches its steady state value much earlier with robust fuzzy logic TCSC compared to conventional Lead lag TCSC and Robust H∞ TCSC controller.

Table- 2: Comparison of lead-lag, robust H∞ tcsc controller and robust fuzzy logic tcsc controller based on settling time.

	Settling time (T_S) in msec		
Parameter of SMIB power system	Lead- lag TCSC controller	Robust H_∞ TCSC controller	Robust fuzzy logic TCSC controller
Speed deviation	24	4	3.8
Terminal Voltage	38	4.8	4.2
Accelerating power	30	3.2	3.3

From the Table-2, it is evident that the robust fuzzy TCSC controller makes the system stable faster than the conventional Lead- lag TCSC and robust H_∞ TCSC controllers.

6. Conclusion

This proposed investigation has described about the various structure of TCSC controllers such as conventional Lead-lag controller, robust H_∞ loop shaping TCSC controller, robust fuzzy logic controller, which are designed and analytically modelled for a Single Machine Infinite Bus (SMIB) power system at the same operating condition. These controller actions are effective in damping the low frequency oscillations resulting from various small disturbances like mechanical power input, terminal voltage setting, and speed deviation. Under these various disturbances, the stability analysis of the proposed system is also carried out. Moreover, comparisons of Lead-lag TCSC, robust H_∞ TCSC and robust fuzzy logic TCSC controllers based on settling time are analyzed. Further, the obtained results show that the system with robust fuzzy logic controller is capable of stabilizing the system faster than the conventional and H_∞ TCSC controllers.

Appendix

Generator: M = 9.26 s., D = 0, X_d = 0.973, X_q = 0.5, X'_d = 0.19, T'_{do} = 7.76, f = 60, V_T =1.05, $X_{TL} + X_T$ = 0.997.

Exciter : K_A = 50, T_A = 0.05 s, T_A = 0.05 s.

TCSC Controller: X_{TCSC} = 0.2169. k=2, $T_1 = T_3$, $T_2 = T_4$, T_{WS}=10 s.

System matrix:

$$A = \begin{bmatrix} 0 & 377 & 0 & 0 \\ -0.2918 & 0 & 0 & -0.1253 \\ 7.21 & 0 & -33.33 & -6.185 \\ 0.421 & 0 & 1.587 & -0.373 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0.312 & 0 \\ -10.53 & 133.33 \\ 0.253 & 0 \end{bmatrix}$$

$$\begin{bmatrix} \Delta V_m \\ \Delta P_m \end{bmatrix} = \begin{bmatrix} -0.031 & 0.1128 & 0.2158 \\ 0.8965 & -0.2166 & 0.6523 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta e'_q \\ \Delta B \end{bmatrix}$$

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