Controlling SSSC by Full Order State Feedback Controller

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ABSTRACT

In this Paper a new approach to design a Full Order State Feedback Controller of Voltage Source Converter (VSC) based SSSC is proposed for improving transient stability of the system. Here Full Order State Feedback Controller is designed by using Pole Placement method. This paper also presents a conventional PI-controller for SSSC where the PI-controller parameters are tuned using Ziegler-Nichols Closed Loop Damped Oscillation method. A detailed comparative analysis is done on the basis of system performance between proposed controller and conventional PI Controller. Simulations have been carried out in MATLAB/SIMULINK Environment.

General Terms

SSSC, Full Order State Feedback Controller, Pole Placement.

Keywords

SSSC, Full Order State Feedback Controller, Pole Placement, PI-controller, Ziegler-Nichols Closed Loop Damped Oscillation.

1. INTRODUCTION

In India, power demand is increasing considerably day by day due to the large population and modernization growth. There are many drawbacks in the quality of power in terms of low power factor, poor power voltage profile, voltage fluctuations etc., which are need to be minimized to shake up power demand. For these reasons, improvement in the capability of power transfer of existing power systems is very important [1].

For improving the capability of power transfer of the existing power systems Power Electronics based Flexible AC Transmission System (FACTS) devices have been developed [1]. FACTS technology is introduced by EPRI (Electric Power Research Institute) in 1980's [2]. FACTS help to increase the power transfer capacity, controllability and also utilize flexibility of ac transmission systems. Static Synchronous Series Compensator (SSSC) is a member of FACTS controllers, acts as a series compensation device of the FACTS family. It is mainly connected in series with power transmission lines and able to exchange both active and reactive power at its output terminals with an ac power system. The main function of SSSC is to control power flow in transmission lines and improve transient stability of power systems [3], [4].

In this paper tuning of conventional PI-controller is done for obtaining the best values of proportional & integral gains for SSSC, so that a comparative analysis can be done between the conventional PI-controller & the proposed Full Order State Feedback Controller in terms of maximum overshoot & settling time of the system.

2. MODELING OF THE SSSC

SSSC mainly consists of a transformer which is connected in series with the transmission line, a voltage source converter with some semiconductor devices having turn off capability for coupling with the transformer and a direct current capacitor. The DC capacitor operates as an energy storage element by providing a DC voltage support for the converter functions. SSSC injects a voltage in series with transmission lines through this coupling transformer [4]. The figure below shows the schematic diagram of SSSC.
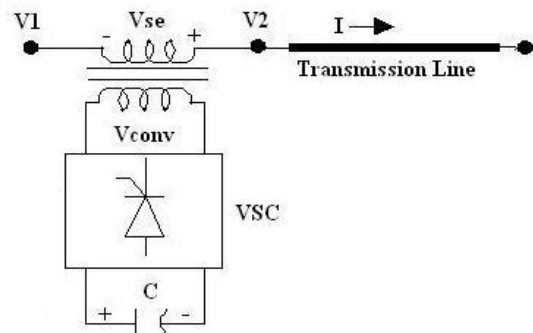

Fig 1: Schematic diagram of SSSC [4]

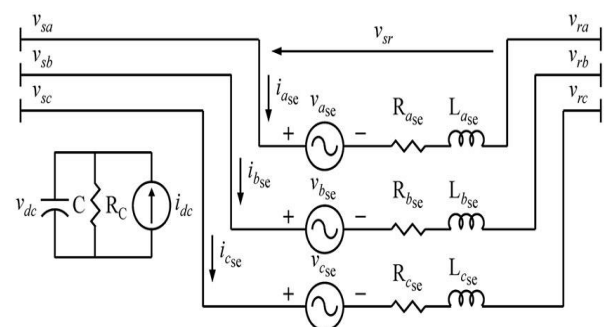In this paper the generalized mathematical model of SSSC has been derived.

Fig 2: Circuit diagram of SSSC [5]

The circuit diagram of SSSC is shown in fig 2. The dynamic equation from fig 2 can be written as [6]

$$\frac{di_{SEa}}{dt} = \frac{V_{Sa} - V_{Ra}}{L_{SEa}} - \frac{R_{SEa}}{L_{SEa}} i_{SEa} + \frac{V_{SEa}}{L_{SEa}} \tag{1}$$

$$\frac{di_{SEb}}{dt} = \frac{V_{Sb} - V_{Rb}}{L_{SEb}} - \frac{R_{SEb}}{L_{SEb}} i_{SEb} + \frac{V_{SEb}}{L_{SEb}} \tag{2}$$

$$\frac{di_{SEc}}{dt} = \frac{V_{Sc} - V_{Rc}}{L_{SEc}} - \frac{R_{SEc}}{L_{SEc}} i_{SEc} + \frac{V_{SEc}}{L_{SEc}} \tag{3}$$

Where, $i_{SEa}, i_{SEb}, i_{SEc}$ are the series converter (SSSC) currents and $V_{SEa}, V_{SEb}, V_{SEc}$ are the series converter voltages for a, b & c phase respectively. V_{Sa}, V_{Sb}, V_{Sc} are the sending end voltages & V_{Ra}, V_{Rb}, V_{Rc} are the receiving end voltages of the three phase system and $R_{SEa}, R_{SEb}, R_{SEc}$ are the resistances & $L_{SEa}, L_{SEb}, L_{SEc}$ are the inductances of series converter for a, b & c phase respectively.

The equations (1), (2), (3) can be written in synchronously rotating d-q reference frame as follows [6]

$$\frac{di_{SEd}}{dt} = -\frac{R_{SE}}{L_{SE}} i_{SEd} + \omega i_{SEq} + \frac{(V_{Sd} - V_{Rd})}{L_{SE}} + \frac{V_{SEd}}{L_{SE}} \tag{4}$$

$$\frac{di_{SEq}}{dt} = -\omega i_{SEd} - \frac{R_{SE}}{L_{SE}} i_{SEq} + \frac{(V_{Sq} - V_{Rq})}{L_{SE}} + \frac{V_{SEq}}{L_{SE}} \tag{5}$$

Since for normal operation of the converter, the dc voltage across the dc storage capacitor C must be kept constant.

$$\frac{dV_{dc}}{dt} = \frac{3}{2CV_{dc}} \left(V_{SEd} i_{SEd} + V_{SEq} i_{SEq} \right) - \frac{V_{dc}}{R_P C} \tag{6}$$

The magnitude of converter voltage and dc voltage across capacitor are proportional to each other.

$$V_{SEd} = (m_{SE} \cos \delta_{SE}) V_{dc}$$

$$V_{SEq} = -(m_{SE} \sin \delta_{SE}) V_{dc} \tag{7}$$

Here, m_{SE} is the modulation index of SSSC and δ_{SE} is phase angle difference between converter voltage & dc voltage.

Now rewriting equations (4), (5), (6) by substituting equation (7) in matrix form as:

$$\frac{d}{dt} \begin{bmatrix} i_{SEd} \\ i_{SEq} \\ V_{dc} \end{bmatrix} =$$

$$\begin{bmatrix} -\frac{R_{SE}}{L_{SE}} & \omega & \frac{m_{SE}\cos\delta_{SE}}{L_{SE}} \\ -\omega & -\frac{R_{SE}}{L_{SE}} & -\frac{m_{SE}\sin\delta_{SE}}{L_{SE}} \\ \frac{3}{2C}(m_{SE}\cos\delta_{SE}) & -\frac{3}{2C}(m_{SE}\sin\delta_{SE}) & -\frac{1}{R_PC} \end{bmatrix} \begin{bmatrix} i_{SEd} \\ i_{SEq} \\ V_{dc} \end{bmatrix} +$$

$$\begin{bmatrix} \frac{1}{L_{SE}} & 0 \\ 0 & \frac{1}{L_{SE}} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} (V_{Sd} - V_{Rd}) \\ (V_{Sq} - V_{Rq}) \end{bmatrix} \tag{8}$$

The linearized state equation of SSSC about the operating point δ_0 [7]

$$\begin{bmatrix} \Delta\dot{I}_{SEd} \\ \Delta\dot{I}_{SEq} \\ \Delta\dot{V}_{dc} \end{bmatrix} \begin{bmatrix} -\frac{R_{SE}}{L_{SE}} & \omega & \frac{m_{SE}}{L_{SE}}\cos\delta_0 \\ -\omega & -\frac{R_{SE}}{L_{SE}} & -\frac{m_{SE}}{L_{SE}}\sin\delta_0 \\ \frac{3m_{SE}}{2C}\cos\delta_0 & -\frac{3m_{SE}}{2C}\sin\delta_0 & -\frac{1}{R_PC} \end{bmatrix} \begin{bmatrix} \Delta i_{SEd} \\ \Delta i_{SEq} \\ \Delta V_{dc} \end{bmatrix} +$$

$$\begin{bmatrix} \frac{1}{L_{SE}} & 0 & -\frac{m_{SE}}{L_{SE}}V_{dc_0}\sin\delta_0 \\ 0 & \frac{1}{L_{SE}} & -\frac{m_{SE}}{L_{SE}}V_{dc_0}\cos\delta_0 \\ 0 & 0 & -\frac{3m_{SE}}{2C}(i_{SEd_0}\sin\delta_0 + i_{SEq_0}\cos\delta_0) \end{bmatrix} \begin{bmatrix} \Delta(V_{Sd} - V_{Rd}) \\ \Delta(V_{Sq} - V_{Rq}) \\ \Delta\delta \end{bmatrix} \tag{9}$$

The steady state operation of SSSC can be done, by setting all derivative terms of its dynamic mathematical model to zero & assuming: $(V_{Sd} - V_{Rd}) = (V_S - V_R), (V_{Sq} - V_{Rq}) = 0, i_{SEd} = I_{SEd}, i_{SEq} = I_{SEq}$. Rewriting ωL_{SE} as X_{SE} steady state equation becomes [8]

$$\begin{bmatrix} -R_{SE} & X_{SE} & m_{SE}\cos\delta_{SE} \\ -X_{SE} & -R_{SE} & -m_{SE}\sin\delta_{SE} \\ 3m_{SE}\cos\delta_{SE} & -3m_{SE}\sin\delta_{SE} & -\frac{2}{R_P} \end{bmatrix} \begin{bmatrix} I_{SEd} \\ I_{SEq} \\ V_{dc} \end{bmatrix} = \begin{bmatrix} (V_S - V_R) \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

Solving I_{SEd}, I_{SEq}, V_{dc}; we get the expressions as

$$I_{SEd} = \frac{R_{SE} - \frac{3}{2}m_{SE}^2 R_P \sin\delta_{SE}^2}{R_{SE}^2 + X_{SE}^2 - \frac{3}{2}R_{SE} m_{SE}^2 R_P} (V_S - V_R) \tag{11}$$

$$I_{SEq} = \frac{-X_{SE} - \frac{3}{2}m_{SE}^2 R_P \sin\delta_{SE}\cos\delta_{SE}}{R_{SE}^2 + X_{SE}^2 - \frac{3}{2}R_{SE} m_{SE}^2 R_P} (V_S - V_R) \tag{12}$$

$$V_{dc} = \frac{\frac{3}{2}m_{SE} R_P (R_{SE}\cos\delta_{SE} + X_{SE}\sin\delta_{SE})}{R_{SE}^2 + X_{SE}^2 - \frac{3}{2}R_{SE} m_{SE}^2 R_P} (V_S - V_R) \tag{13}$$

3. CONTROL OF SSSC
In this paper for improving the performance of SSSC as well as the system various control strategies have been developed, which can give better results than the conventional PI controller.

3.1 Proportional–Integral (PI) control
PI controller is mostly used to minimize the steady state error causing from the P controller. The closed loop system with PI – controller is shown in fig 3.
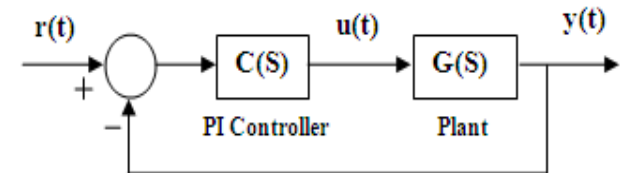

Fig 3: Block diagram for PI – controller based system [9]

To get the most appropriate values for proportional & integral gain i.e. K_p, K_i of the PI – Controller, controller has been tuned using Ziegler-Nichols closed loop damped oscillation method. This method is applicable to those closed loop systems which are not allowed to undergo through sustained oscillations. According to this method, system is initially

operated with low proportional gain with integral time constant, $\tau_i \cong \infty$. The proportional gain is increased slowly till a decay ratio (A_2/A_1) i.e. the ratio of the amplitudes of subsequent peaks in the same direction is equal to or near about ¼ is obtained in step response of the output, as shown in fig 4. [9], [10], [11].
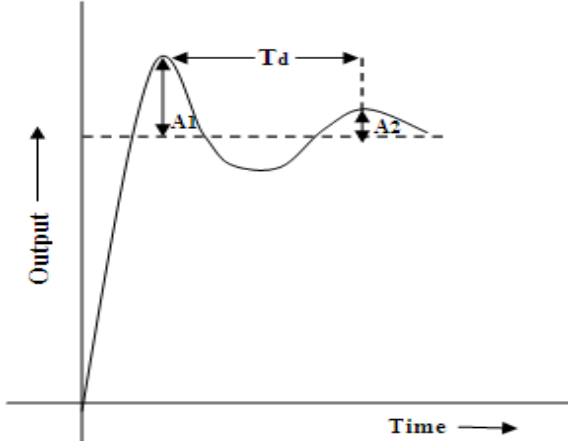

Fig 4: Controller tuning using damped oscillation technique [9]

Under this condition the system is considered as a stable system and the period of damped oscillation, T_d is also noted. Let G_d be the proportional gain setting for obtaining the desired decay ratio [11]. The optimum setting for a P-I controller is, $\mathbf{K_p = 1.1G_d}; \tau_i = \frac{T_d}{2.6}$ [11]. Here PI-controller parameters have been tuned for controlling current as well as voltage of SSSC. The block diagram designs of SSSC with PI-controller are shown in fig 5 & 6 respectively.
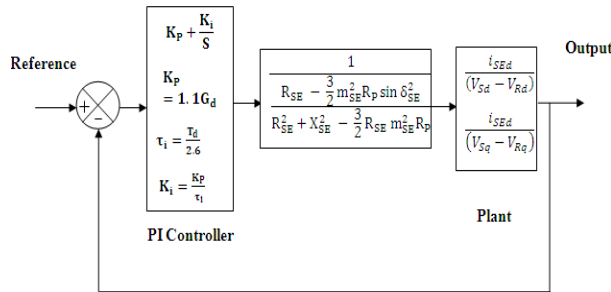

Fig 5: Block diagram of SSSC with PI – controller (current control)

This is the block diagram for controlling current of SSSC; here plant is simply represented by the transfer functions of SSSC:

$$\frac{i_{SEd}}{(V_{Sd} - V_{Rd})} =$$

$$\cfrac{2L_{SE}CR_PS^2+S(2CR_{SE}R_P+2L_{SE})+(-3m_{SE}^2\sin\delta^2 R_P+2R_{SE})}{2L_{SE}^2CR_P\left\{\begin{array}{l}S^3+\left(\frac{2R_{SE}}{L_{SE}}+\frac{1}{R_PC}\right)S^2+\left(\frac{R_{SE}^2}{L_{SE}^2}+\frac{2R_{SE}}{L_{SE}CR_P}+\omega^2-\frac{3m_{SE}^2}{2L_{SE}C}\right)S+ \\ \left(\frac{R_{SE}^2}{L_{SE}^2CR_P}-\frac{3m_{SE}^2 R_{SE}}{2CL_{SE}^2}+\frac{\omega^2}{R_PC}\right)\end{array}\right\}} \tag{14}$$

$$\frac{i_{SEd}}{(V_{Sq} - V_{Rq})} =$$

$$\cfrac{S\omega/L_{SE}+(\omega/L_{SE}CR_P-3m_{SE}^2\sin\delta\cos\delta/2L_{SE}C)}{\left\{\begin{array}{l}S^3+\left(\frac{2R_{SE}}{L_{SE}}+\frac{1}{R_PC}\right)S^2+\left(\frac{R_{SE}^2}{L_{SE}^2}+\frac{2R_{SE}}{L_{SE}CR_P}+\omega^2-\frac{3m_{SE}^2}{2L_{SE}C}\right)S+ \\ \left(\frac{R_{SE}^2}{L_{SE}^2CR_P}-\frac{3m_{SE}^2 R_{SE}}{2CL_{SE}^2}+\frac{\omega^2}{R_PC}\right)\end{array}\right\}} \tag{15}$$
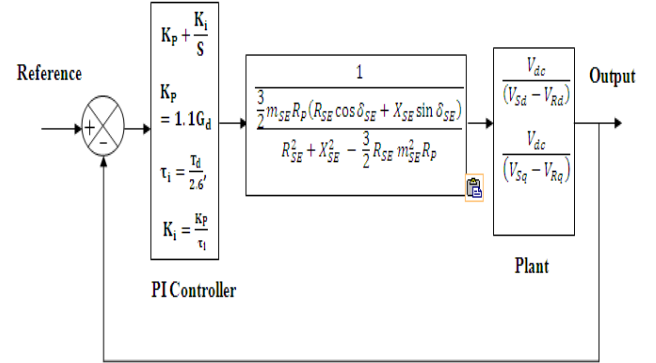

Fig 6: Block diagram of SSSC with PI – controller (voltage control)

This is the block diagram for controlling voltage of SSSC; here also plant is simply represented by the transfer functions of SSSC:

$$\frac{V_{dc}}{(V_{Sd}-V_{Rd})} = \cfrac{3m_{SE}\cos\delta L_{SE}S+3\omega m_{SE}\sin\delta L_{SE}+3m_{SE}\cos\delta R_{SE}}{2L_{SE}^2C\left\{\begin{array}{l}S^3+\left(\frac{2R_{SE}}{L_{SE}}+\frac{1}{R_PC}\right)S^2+ \\ \left(\frac{R_{SE}^2}{L_{SE}^2}+\frac{2R_{SE}}{L_{SE}CR_P}+\omega^2-\frac{3m_{SE}^2}{2L_{SE}C}\right)S+ \\ \left(\frac{R_{SE}^2}{L_{SE}^2CR_P}-\frac{3m_{SE}^2 R_{SE}}{2CL_{SE}^2}+\frac{\omega^2}{R_PC}\right)\end{array}\right\}} \tag{16}$$

$$\frac{V_{dc}}{(V_{Sq}-V_{Rq})} =$$

$$\cfrac{-3m_{SE}\sin\delta L_{SE}S+3\omega m_{SE}\cos\delta L_{SE}-3m_{SE}\sin\delta R_{SE}}{2L_{SE}^2C\left\{\begin{array}{l}S^3+\left(\frac{2R_{SE}}{L_{SE}}+\frac{1}{R_PC}\right)S^2+ \\ \left(\frac{R_{SE}^2}{L_{SE}^2}+\frac{2R_{SE}}{L_{SE}CR_P}+\omega^2-\frac{3m_{SE}^2}{2L_{SE}C}\right)S+ \\ \left(\frac{R_{SE}^2}{L_{SE}^2CR_P}-\frac{3m_{SE}^2 R_{SE}}{2CL_{SE}^2}+\frac{\omega^2}{R_PC}\right)\end{array}\right\}} \tag{17}$$

3.2 Full order state feedback controller by pole placement method

Pole placement is a method by which a linear system can be stabilized along with a satisfactory response by placing the closed loop poles into desired locations. The objective of placing the closed loop poles into desired locations is achieved by using State Feedback in which the state vectors of the system are feed backed through a gain matrix as input vectors. So it is obvious in designing State feedback controller, all the states of the system should be available or measureable for feedback. This leads to the design of State Observer System [12] which estimates the states of the system based on the measurements of output variables over a period of time. It is of two kinds – full order and reduced order. Here

full order state observer system has been considered as it estimates all the states of the system. The block diagram of SSSC with full order state feedback controller is shown in fig 7.
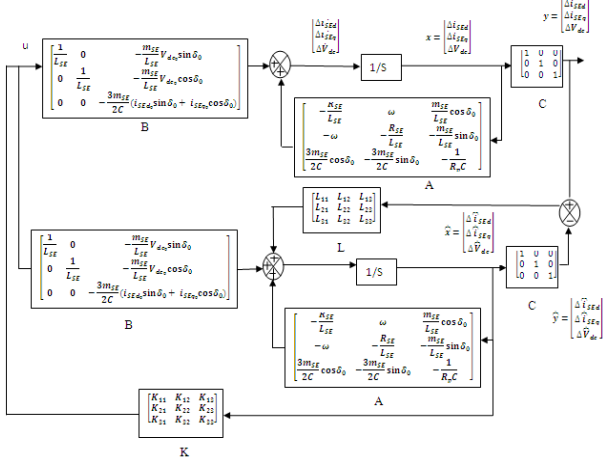

Fig 7: Block Diagram of SSSC with Full Order State Feedback Controller

Open loop system dynamics of the plant can be expressed as

$$\dot{X} = AX + Bu$$

As the estimated states are being feed backed, then the control law is

$$u = -K\hat{X}$$

Error dynamics of the observer system is

$$\dot{E} = (A - LC)E$$

Now, combined system dynamics of the whole system is

$$\begin{bmatrix} \dot{X} \\ \dot{E} \end{bmatrix} = \begin{bmatrix} A - BK & BK \\ 0 & A - LC \end{bmatrix} \begin{bmatrix} X \\ E \end{bmatrix}$$

So, the characteristic equation of the system is

$$|SI - (A - BK)||SI - (A - LC)| = 0 \qquad (18)$$

Here, $|SI - (A - BK)| = 0$ represents the closed loop characteristic equation for State Feedback Controller & $|SI - (A - LC)| = 0$ represents the characteristic equation for State Observer. In order to design the gain matrix K of state feedback controller as well as the gain matrix L of state observer for the system, both the equation need to be solved with the help of desired characteristic equations form by the known desired locations of closed loop poles & known desired locations of observer poles respectively.

3.2.1 Determination of closed loop poles
A well performed system is bounded by maximum limits of settling time (t_s) & maximum overshoot $(\%OS)$ expressed as

$$\%OS = 100 * e^{\left(\frac{-\xi\pi}{\sqrt{(1-\xi^2)}}\right)} \ \& \ t_s = \frac{4}{\xi\omega_n} \qquad (19)$$

Where, ξ is damping ratio & ω_n is natural frequency [7]. From these values the system desired pole locations are selected as, real part of the system $-\sigma = -\xi\omega_n$ (20)

& imaginary part of the system $\pm j\omega = \pm j\omega_n \sqrt{(1 - \xi^2)}$ (21)

3.2.2 Determination of observer Eigen values
The observer Eigen values should be chosen near about ten times faster than the system Eigen values. This can be done by placing the smallest real part of the observer Eigen values ten times bigger than the largest real part of the closed-loop system Eigen values. Therefore,

$$|Re\{\lambda_{min}(A - LC)\}|_{observer} > 10|Re\{\lambda_{max}(A - BK)\}|_{system}$$
[13]   (22)

4. CASE STUDY
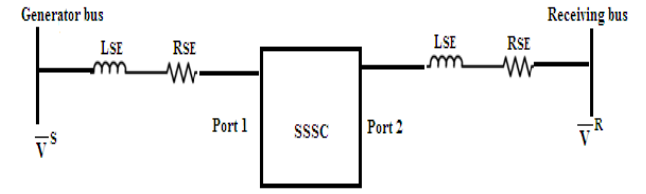The system under consideration is shown in fig 8.

Fig 8: System under study

The system data for SSSC are: [14], [15], [16]

$X_{SEp.u} = 0.075, R_{SEp.u} = 0.0075,$

$g_{capp.u} = 0.02, b_{capp.u} = 2$

$m_{SE} = 0.08, V_{Sp.u} = 1.0\angle30, V_{Rp.u} = 1.0\angle0$

Base MVA$(S_{base}) = 160$ MVA,

Base Voltage $(V_{base}) = 37$ KV.

5. SIMULATION RESULTS
5.1 Proportional–Integral (PI) control
By tuning the PI-controller parameters current as well as voltage of SSSC has been controlled.

5.1.1 Simulation of PI - controller for controlling current of SSSC
After simulation following results have been found for SSSC: Fig 9.and fig 10.shows the steady state error and output current i_d of the system respectively and following parameters have been found after tuning PI-controller as shown in table 1
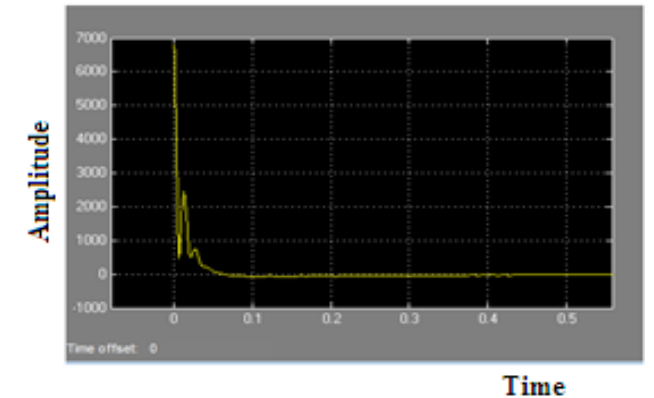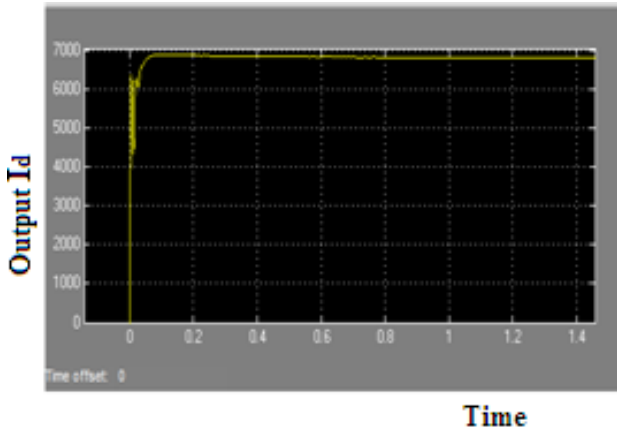

Fig 9: Simulation graph for error signal

Fig 10: Simulation graph for output current I_d

Table 1. Parameters obtained after tuning PI-controller for SSSC (controlling current)

G_d	T_d	τ_i	K_P	K_i
0.4	0.0163s	$\tau_i = \frac{T_d}{2.6}$ $= 6.25e^{-3}$	$0.\times 1.1$ $= 0.44$	$K_i = \frac{K_p}{\tau_i} =$ 70.4

The system has maximum overshoot, M_P & settling time, t_S of 2% & 0.09s respectively.

5.1.2 Simulation of PI - controller for controlling voltage of SSSC

Fig 11.and fig 12.shows the steady state error and output voltage V_{dc} of the system respectively and following parameters have been found after tuning PI-controller as shown in table 2.
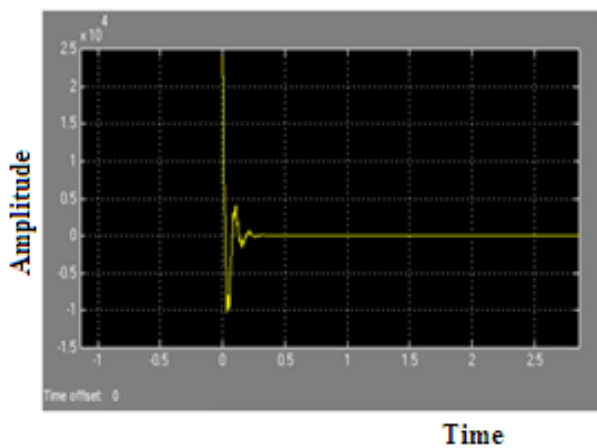

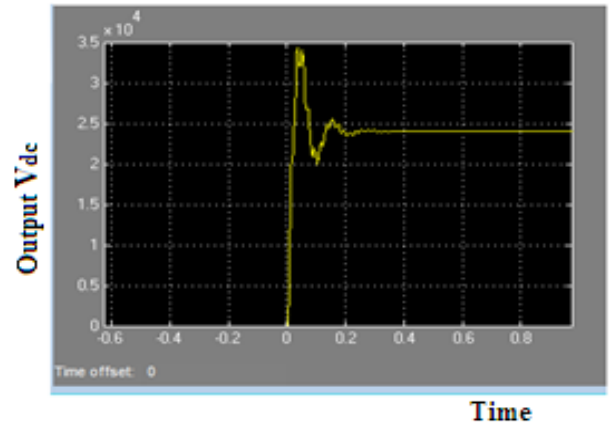**Fig 11: Simulation graph for error signal**

Fig 12: Simulation graph for output voltage V_{dc}

Table 2. Parameters obtained after tuning PI-controller for SSSC (voltage current)

G_d	T_d	τ_i	K_P	K_i
0.09	0.0203s	$\tau_i = \frac{T_d}{2.6}$ $= 7.78e^{-3}$	$0.09 \times 1.$ $=0.099$	$K_i = \frac{K_p}{\tau_i}$ $=12.72$

The system has maximum overshoot, M_P & settling time, t_S of 41.67% & 0.25s respectively.

5.2 Full order state feedback controller by pole placement method

5.2.1 Determination of closed loop poles for SSSC

The system control specifications i.e. the maximum limits of settling time (t_s) & maximum overshoot (%OS) for desired response of the system considered is selected as 0.01 s & 5 % respectively. These result in $-\sigma = -\xi\omega_n = -399.99$ & $\pm j\omega = \pm j\omega_n\sqrt{(1 - \xi^2)} = \pm j419.48$.

5.2.2 Determination of observer Eigen values for SSSC

The observer Eigen values has been chosen by placing the smallest real part of the observer Eigen values ten times bigger than the largest real part of the closed-loop system Eigen values. These result in $-\sigma = 10 * -399.99$ & $\pm j\omega = 10 * \pm j419.48$.

Fig 13. shows the graph of error signals of the system which means the difference between plant output and observer output. From this fig it can be observed that the error signals of three states are reduced to zero, so the proposed controller can minimize the error.

Fig 14. is the graph of plant states and observer states. From this graph it can be observed that the states of the plant ($i_{SE_d}, i_{SE_q}, V_{dc}$) and the states of observer ($i_{SE_{d_o}}, i_{SE_{q_o}}, V_{dc_o}$) converged with each other after some time which means the observer is working properly

Fig 15.shows the graph of the outputs of the system considering initial conditions for states, $i_{SE_{d_0}} = 1, i_{SE_{q_0}} = -2$ & $V_{dc_0} = 5$. Observations from Fig. 15 are shown in Table 3.
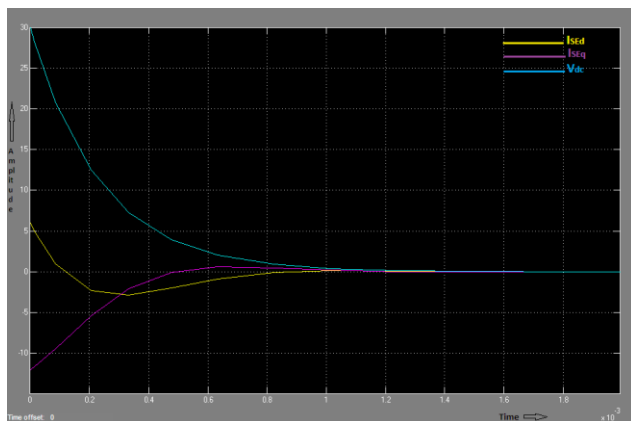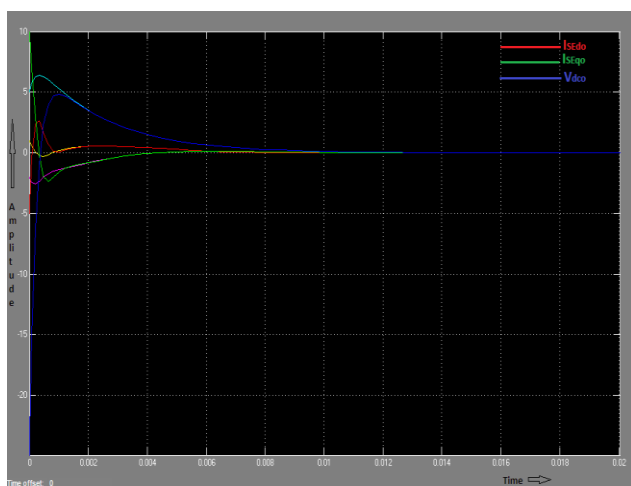

Fig 13: Graph of error signal
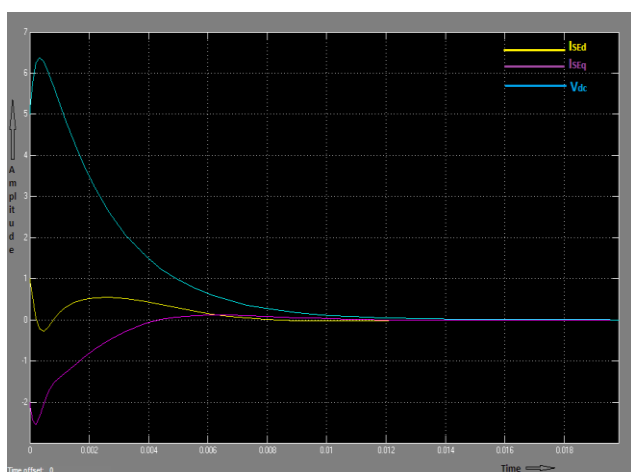

Fig 14: Graph of plant states and observer states

Fig 15: Output graph of SSSC

Table 3: Observations of output signal of SSSC

System outputs	Maximum overshoot	Settling time
i_{SE_d}	0.63 %	0.007 s
i_{SE_q}	0.18 %	0.01 s
V_{dc}	6.45%	0.011 s

6. CONCLUSION

Increasing energy costs and a greater sensitivity to the environmental impact of new transmission lines demanded the search and application of new controllers to minimise the losses and maximise the stable power transmission capacity of existing lines along with voltage stability. Hence FACTS controllers are becoming an integral component of modern power transmission systems. Controller plays an important role for compensating the system during contingency analysis. This thesis is intended to create an awareness of control issues and has proposed controller for SSSC. In this work first of all a conventional PI controller by proper tuning has been designed for SSSC. The reason behind of tuning is comparative analysis of system performance between the proposed controller and the conventional one.

The research work concentrated on controller design of SSSC. Full order state feedback controller is designed by using Pole Placement method. In this thesis new controller i.e. full order state feedback controller for VSC based SSSC is analyzed and found very effective. It is seen from the simulation result that new proposed controller gives better performance during contingency condition. Besides this, it has been observed from the analysis that the proposed controller is efficient and can provide fast dynamic response to the system than conventional SSSC PI controller.

7. ACKNOWLEDGMENTS

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