STUDY OF SMALL SIGNAL STABILITY WITH STATIC SYNCHRONOUS SERIESCOMPENSATOR FOR AN SMIB SYSTEM

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Abstract - ***Small signal stability problems due to low frequency electromechanical oscillations are inherent phenomena of interconnected power systems which reduce the available transfer and total transfer capability. Recent development of power electronics introduces the use of flexible ac transmission system (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the voltage stability, and steady state and transient stabilities of a complex power system . The static synchronous series compensator (SSSC) is one of the series FACTS devices based on a solid-state voltage source inverter (VSC) which generates a controllable ac voltage in quadrature with the line current.In this thesis a Single machine infinite Bus (SMIB) system modeling is done and small signal stability analysis of the system with capacitor alone and fixed injection SSSC is done from the eigenvalue analysis. Controller is designed for SSSC from the eigen value analysis and then stability analysis is done with this controller.***

Key Words: *sssc controller,eigenvalues,small signal stability etc..*

1. INTRODUCTION

At present the demand for electricity is rising phenomenally especially in developing country like India. This persistent demand is leading to operation of the power system at its limit. On top of this the need for reliable, stable and quality power is also on the rise due to electric power sensitive industries like information technology, communication, electronics etc. In this scenario, meeting the electric power demand is not the only criteria but also it is the responsibility of the power system engineers to provide a stable and quality power to the consumers. These issues highlight the necessity of understanding the power system stability. A power system is steady state stable for a particular steady state operating condition if, following any small disturbance, it reaches a steady state operating condition which is identical or close to the pre-disturbance operating condition .This is carried out by considering the system in linearized form.

Hingorani proposed the concept of FACTS (Flexible AC Transmission Systems) using solid state devices to achieve flexibility of system operation with fast and reliable control.The purpose of these devices are to utilize the prevailing transmission system to its best extent, because what normally happens is that the power system network operates much below its full capacity. The basic power system

2. MODELLING OF THE SYSTEM

The models of the major components of the power system that determines its dynamic behavior are discussed in this chapter. For the present project work a SMIB (single machine connected to an infinite bus) system is undertaken. This system can be considered for study because it can represent a complex interconnected network if the rest of the system is presented by the Thevenin's equivalent. Study of such a simplified system can also predict the behavior of complex interconnected network. The system connected is a two port network, in which one of port is connected to the generator terminals while the second port is connected to a voltage source ($E_b\angle 0$), whose magnitude and phase angle does not change with time, so it is called the infinite bus.

One of the major assumptions in study low frequency oscillation i.e. oscillation frequency less than (5HZ), is to neglect the transients in the external network. This simplifies the analysis as the network is modeled by algebraic equations. If network transients are neglected, it is logical to ignore the transients in the stator winding of the synchronous machine which are connected to the external network . the network equations are conveniently expressed in D-Q reference frame and the general equations in d-q reference frame , so before solving these nonlinear equations it is necessary to represent these equations in any one reference frame. In this project work it is done in d-q reference frame.

2.1 Generator Equations

$$\frac{d\delta}{dt} = \omega_B(S_m - S_{mo})$$

$$\frac{dS_m}{dt} = \frac{(-D(S_m - S_{mo}) + T_m - T_e)}{2H}$$

$$\frac{dE_q^{'}}{dt} = \frac{1}{T_{d0}^{'}}\left[-E_q^{'} + (x_d - x_d^{'})i_d + E_{fd}\right]$$

$$\frac{dE_d^{'}}{dt} = \frac{1}{T_{q0}^{'}}\left[-E_d^{'} - (x_q - x_q^{'})i_q\right]$$

$$\frac{dE_{fd}}{dt} = \frac{1}{T_A}\left[-E_{fd} + K_A(V_{ref} - V_g + V_s)\right]$$

$$\frac{dx_1}{dt} = -{x_1}/{T_w} + {S_m}/{T_w}$$

$$\frac{dV_{sssc}}{dt} = \frac{-V_{sssc} + V_{sssc_{ref}}}{T_{sssc}}$$

2.2 Network Equations

$$V_q = R_e I_q - x_e I_d + h_1 E_b \cos\delta + h_2 E_b \sin\delta$$

$$V_d = x_e I_q + R_e I_d + h_2 E_b \cos\delta - h_1 E_b \sin\delta$$

2.3 Equation of AVR

$$\frac{dE_{fd}}{dt} = \frac{1}{T_A}\left[-E_{fd} + K_A(V_{ref} - V_g + V_s)\right]$$

2.4 Equations Relating To SSSC In Network

$$V_q = R_e I_q - x_e I_d + h_1 E_b \cos\delta + h_2 E_b \sin\delta - V_{sssc}\cos\beta$$

$$V_d = x_e I_q + R_e I_d + h_2 E_b \cos\delta - h_1 E_b \sin\delta - V_{sssc}\sin\beta$$

$$\beta = arc\tan\left(\frac{I_d}{I_q}\right) + \frac{\Pi}{2}$$

2.5 SSSC Controller Equation

$$\frac{dx_1}{dt} = -{x_1}/{T_w} + {S_m}/{T_w}$$

$$\frac{dx_2}{dt} = (-x_2/T_b) + \frac{(S_m - x_1)K_s(T_b - T_a)}{{T_b}^2}$$

$$\frac{dV_{sssc}}{dt} = \frac{-V_{sssc} + V_{sssc_{ref}}}{T_{sssc}}$$

3. SMALL SIGNAL STABILITY ANALYSIS

Linearizing the generator equations and writing in state space form the following set of equations are obtained

$$\dot{x}_m = A_m x_m + B_{m1}\Delta I_m + B_{m2}\Delta E_{fd} + B_{m3}\Delta T_m$$

The controller equations in general can be expressed as

$$\dot{x}_c = A_c x_c + B_{c1}\Delta V_m + B_{c2}\Delta S_m + E_c u_c$$

Combining the machine and controller equations and representing in state space form the new state matrix in presence of the controller is given by

$$\dot{x}_g = A_g x_g + B_{g1}\Delta I_m + B_{g2}\Delta V_m + E_g u_c$$

For the SMIB system the linearized relationship between voltage and current from is given by

$$\Delta V_m = Z\Delta I_m + A\,\Delta\delta$$

If the voltage sources is controllable then the following extra matrix is required for finding the eigenvalues of the system matrix, as it will introduce terms containing ΔV_{sssc} .The new linearized network equation will be of the from

$$V_m = Z\Delta I_m + A\,\Delta\delta + S\,\Delta V_{sssc}$$

3.1 Derivaon of System Equations

The system equations are obtained by eliminating ΔI_m and ΔV_m from the stator and network equations and representing ΔI_m in terms of the state vectors

$$\Delta I_m = F_i x_g$$

where

$$F_i = Z_T^{-1}(C_E - Ae_1$$

$$Z_T = (Z + Z_g)$$

$$\left[\Delta E_q^{'}\ \Delta E_d^{'}\right]^t = C_E x_g$$

$$\Delta\delta = e_1 x_g$$

$$\Delta V_m = F_v x_g$$

$$F_v = ZF_i + Ae_1$$

If SSSC has to be introduced into the network the following linearized network equation has to be considered.

$$F_i = Z_T^{-1}(C_E - Ae_1 - Se_8)$$

$$F_v = ZF_i + Ae_1 + Se_8$$

$$\Delta V_{sssc} = e_8 x_g$$

Now the overall state matrix representation is of the form

$$\dot{x}_g = A_{c\ T} x_g + E_c u_c$$

where

$$A_T = A_g + B_{g1}F_i + B_{g2}F_v$$

The system eigenvalues are obtained by solving the characteristic equation of the matrix A_T. The eigenvalues help in finding out whether the given operating point is stable or not. The system is stable if all the eigenvalues lie in the left half plane, if any of the eigenvalues lie in the right half plane then the system may become unstable. If at all the system is unstable then from the eigenvalues analysis we can find out the controller parameters which will make the system stable

3.2 Eigenvalues

The eigenvalues that are obtained with different operating conditions are given in a tabular form .The eigenvalues with E_b=1.0 p.u is shown in Table-1

Table-1: Eigenvalues with Fixed Capacitor alone with E_b=1.0 p.u

Without AVR	With AVR
-0.2747 ± j5.6732	-20.4451 ±j19.4391
-3.0857	-0.1610 ± j6.0286
-0.0854	-2.5083

Table-2: Eigenvalues with Fixed Capacitor alone with E_b=1.01 p.u

Without AVR	With AVR
-0.2737 ± j5.7015	-20.5476 ±j19.2092
-3.0787	-0.1600 ± j6.0595
-0.0840	-2.7073

Table-1 shows the eigenvalues of a SMIB system with fixed capacitor alone and it shows that all the eigenvalues lie in the left of the complex plane, so the operating point is stable with the introduction of fixed capacitor x_c =50% compensation in the line having reactance x_e=0.7 p.u with E_b=1.01 p.u and E_b=1.0 p.u. In place of a fixed capacitor if a SSSC of equivalent voltage is introduced, the eigenvalues that are obtained are listed in Table-3

Table-3: Eigenvalues with Fixed voltage injection SSSC with E_b=1.0 p.u

Without AVR	With AVR
-0.5650 ± j7.9169	-21.1301 ±j14.9896
-4.7486	0.1551 ± j8.8286
-0.0901	-4.0187

Table-4: Eigenvalues with Fixed voltage injection SSSC with E_b=1.01 p.u

Without AVR	With AVR
-0.5651 ±j7.9568	-21.1358 ±j14.9929
-4.7483	0.1600 ± j8.8721
-0.0851	-4.0171

In the case of fixed voltage injection in the line system initial operating point is not stable which is clear from the eigenvalues i.e. real part of all the eigenvalues are notnegative.The Table-3 shows the eigenvalues of the system,where instead of a fixed capacitor,a fixed voltage source whose magnitude is same as the voltage introduced by a fixed capacitor i.e V_{sssco} =x_c I_{go} .The eigenvalues for the system with E_b=1.01 p.u and in presence of SSSC will definitely be unstable which is shown in Table-4

4.CONTROLLER DESIGN

When the capacitor is replaced by a voltage source whose initial voltage magnitude is equal to that of the voltage introduced by the capacitor i.e x_c $I_{go,}$ some of the eigenvalues lie in the right half of the complex plane i.e the real part of some of the eigenvalues are positive,which shows the operating point is unstable with a fixed voltage injected SSSC. This shows that a fixed voltage source is not sufficient to provide the damping necessary for system stability. So the proposed model of a variable voltage source came into discussion.

4.1 Determination Of Controller Parameters

Fig.2 shows the block diagram of the slip input controller .In order to tune the parameters of the controller , the transfer function relating torque and the output of the controller is found out when the change is speed is assumed to be zero. Fig.2 shows the placement of the controller block in the system , the GEP(s)shows the input output relation between the torque and the output of the controller for the variation in speed to be zero. This can be represented in states space form as given below.

$$\dot{x}_r = A_r x_r + B_r \Delta V_{sssc_{ref}}$$

$$\Delta T_e = C_r x_r + D_r \Delta V_{sssc_{ref}}$$

Where

$$x_r = [\Delta E'_q \ \Delta E'_d]$$

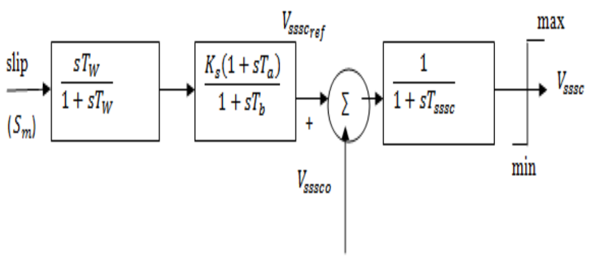

Fig-1: SSSC Controller Block Diagram

From the states space representation

$GEP(s)=C_r(sI - A_r)^{-1}B_r$

States space representation of the machine, excitation controller, and network are considered for finding out the A_r, B_r, C_r. D_r matrices.

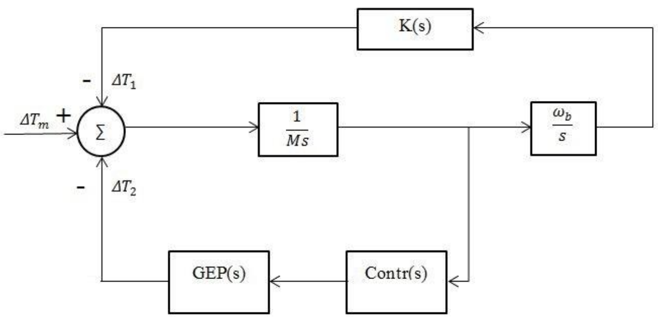

Fig-2: System block diagram

5.BODE PLOTS AND ROOT LOCI

The input-output relation between ΔT_e and $\Delta V_{sssc_{ref}}$ in states space form is derived in the previous section. The Bode plot is drawn in MATLAB, to know the phase lead or lag provided by the system with variation of frequency.

5.1 Design Criteria

1. The time constants are to be chosen from requirements of phase compensation to achieve damping. The compensated phase lead at local mode frequency should be below 45 , preferably near 20 .
2. The gain of the controller should be chosen to provide damping to all critical modes under different operating conditions.

Table-5:Eigenvalues with variable voltage injection SSSC with E_b=1.0 p.u.and K_s=0

With SSSC
-21.1058 ±j16.1771
0.4077 ±j6.4025
50.0000
-3.2518
-1.0000
-0.1000

From the bode plot ,the phase lead or lag at rotor oscillation frequency is obtained. This gives the information about the phase lead or lag to be introduced at that frequency. It is found out to be approximately near value to the specified amount as mentioned in the design criteria. So the phase lead or lag is not necessary. For sake of simplicity T_a=1 sec,T_b=1 sec.The other data of the controller are T_{sssc}=20 milisec,T_w=10 sec. Now the eigenvalues with this variable series voltage source are obtained with the variation of gain K_s over a wide range.With gain K_s=0,the system eigenvalues are shown in the Table-5.When Ks is changed it is found that only one eigenvalue is near the imaginary axis and it becomes unstable with the increase in gain K_s . This critical eigenvalue is plotted for the variation of gain ks. It is shown in Fig 4.From this the root locus gain(K_s) for which the real part of the critical eigenvalue has the maximum negative value is found out and it is around 70. So selecting the gain K_s =70, and $T_a = T_b$ = 1.0 sec,the eigenvalues are found out and tabulated in Table-2 and 3 show the eigen values of the system with the controller for E_b = 1.0 p.u and E_b = 1.01 p.u .

Table-6:Eigenvalues with variable voltage injection SSSC with E_b=1.0 p.u.and K_s=70

With SSSC
-20.8987 +j17.0518
-2.1808 +j 3.9478
-40.6706
-7.8178
-1.0000
-0.1006

Table-7:Eigenvalues with variable voltage injection SSSC with E_b=1.01 p.u.and K_s=70

With SSSC
-20.9032 +j17.0529
-2.2023 + j3.9791
-40.6736
-7.7628
-1.0000
-0.1006

Table-6 and Table-7show that all the eigenvalues of the system are in the left half of the complex plane which show that the system is stable after the controller is added to the system.In this case the voltage,that is injected is synthesized from slip of the generator,this may be difficult to achieve in practical conditions,but gives a fair idea of the improvement in stability after the controller is added. In practical case current controller can be used which is not discussed in the project work.

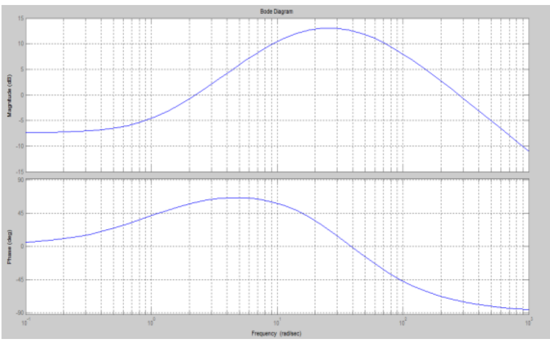

Fig-3: Bode plot of system with no compensator

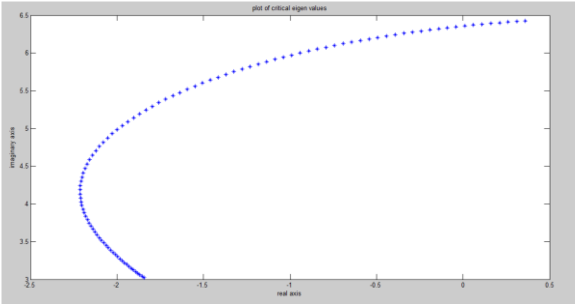

Fig-4 :Root loci for gain determination

6. CONCLUSION

The Static Series Synchronous Compensator (SSSC) offers an alternative to conventional series capacitor line compensation. The series line capacitance is an impedance the produces the required compensating voltage in proportional to the line current flowing through it, in contrast the SSSC is a solid-state voltage source that generates the required compensating voltage independent of the magnitude of the line current. This device can also be used in the presence of a capacitor. Small Signal Stability analysis results show that system is stable when the controller is added to the circuit . This result substantiate the improvement that is achieved by SSSC, which is better than a fixed capacitor used in the circuit.

ACKNOWLEDGMENT

If words are considered as symbol of approval and tokens of knowledge, then let the word play the heralding role of expressing my gratitude.

I would like to express my deepest gratitude to our guide, Dr. T. R. JYOTHSNA, professor, Department of Electrical Engineering, Andhra University College of engineering, Visakhapatnam, for her guidance. I shall always cherish our association for her encouragement, approachability and freedom of thought and action which I had enjoyed during this work.

I'm thankful to Dr. V. BAPI RAJU, professor and head of the department, department of electrical engineering, Andhra University College of Engineering, for providing me all kinds of facilities in the department.

REFERENCES

[1] L.Gyugyi,"Unified power-flow control concept for flexible AC transmission systems.",*IEE Proceedings-C, Vol.139, No.4, July 1992, pp.323-331*.

[2] C.Schauder and H.Mehta,"Vector analysis and control of advanced static VAR compensator." ,*IEE Proceedings-C, Vol.140, No.4, July 1993, pp.299-306.*

[3] L.Gyugyi,"Dynamic compensation of AC transmission lines by solid state synchronous Voltage sources.", *IEEE Transactions on Power Delivery, Vol.9, No.2, April 1994, pp.904-911.*

[4] L.Gyugyi,"The Unified Power Flow Controller: A new approach to power transmission control." , *IEEE Transactions on Power Delivery, Vol.10, No.2, April 1994, pp.1085-1099.*

[5] R.Mihalic, P.Zunko and D.Povh,"Improvement of Transient Stability using Unified Power Flow Controller.", *IEEE Transactions on power Delivery, Vol.11, No.1, January 1996,pp.485-492.*

[6] L.Gyugyi,"Static Synchronous Series Compensator : A solid state approach to the series compensation of AC transmission lines." , *IEEE Transactions on Power Delivery, Vol.12, No.1, January 1997, pp.406-417.*

[7] C.J.Hatziadoniu and A.K. Funk,"Development of a control scheme for a series connected solid state Synchronous Voltage Source."*IEEE Transactions on power Delivery, Vol.11, No.2, April 1996,pp.1138-1144.*

[8] N.G.Hingorani,"FACTS-Flexible AC Transmission Systems."IEEE spectrum,pp.40-45,April 1993.

[9] T.Kailath, "Linear Systems.", Prentice Hall Inc., Englewood Cliffs,N.J.,1980.

*[10]*K.R.Padiyar, "Power System Dynamic Stability and Control."Interline publishing Ltd.,Banglore, India,1996.

*[11]*MATLAB Users Guide, "The Mathworks Inc." The Mathworks press, Natick, Mass.,1995.