DYNAMIC PERFORMANCE ENHANCEMENT OF SERIES COMPENSATED TRANSMISSION LINES USING STATIC VAR SYSTEM

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of

Degree of

MASTERS OF ENGINEERING IN
ELECTRICAL ENGINEERING (POWER APPARATUS & SYSTEMS)

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CERTIFICATE

Dynamic Performance Enhancement of Series Compensated Lines using Static VAR System is a dissertation work submitted in partial fulfillment of the requirement for the award of degree of Masters of Engineering in Power Apparatus & Systems in Delhi College of Engineering, University of Delhi by Kusum Lata.She has worked for this dissertation under my guidance and the work has not been submitted elsewhere for a degree.

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ABSTRACT

Flexible Alternating current transmission system (FACTS) devices are used widely for the dynamic control of voltage, impedance and phase angle of high voltage AC lines.

Thus with Facts controllers the existing transmission facility can be fully utilized and hence minimizing the gap between stability limit and thermal stability.

Series Compensation has been widely used to enhance power transfer capability. However, series compensation gives rise to the problems of dynamic instability and sub synchronous resonance (S.S.R) [1, 2, 3]. Mitigation of low frequency oscillations is one of the most important and challenging tasks in power industry as the stability of these oscillations is a prerequisite for secure and stable operation of power system. Many preventive measures to cope with dynamic instability problem in series compensated lines have been reported in literature [7]. Among these the application of Static Var Systems(SVS) controller has gained the importance in recent years in modern power systems due to its capability to work as Var generator and absorption systems[8,9,10].Besides voltage control and improvement of transmission capability SVS in coordination with auxiliary signals can be used for damping of power system oscillations effectively[11,12].The selection of location of an effective location and feedback signal is an important aspect to employ FACTS controllers[14].It is often seen that the control of SVS has not been demonstrated over a wide operating range[15,16].It requires an effective SVS controller to be developed which is applicable over a wide operating range and under large disturbance conditions.

The controlled series compensation is one of the novel techniques proposed under FACTS concepts. But investigations on how to coordinate these devices for improving stability and damping sub synchronous resonance are still in implementation stage and needs investigation. A detailed system model which can reflect system dynamics accurately over a wide operating range has to be

developed. Proper location of SVS and Series compensation play a very important role for enhancement of dynamic and transient stability of power system[18].Thus there is need to determine the optimal location of static var system and the amount of series compensation in the power systems. Also the rating of SVS should be based on steady state analysis because SVS may cause high power transfer level over long distance.

Different types of SVS auxiliary signals and their combination have been tried to find out the most effective auxiliary signal or effective combination for enhancement of dynamic and transient performance over a wide operating range.

A detailed system model has been developed for the dynamic and transient performance of the system (Chapter -2). The study system consists of a generator supplying power to an infinite bus over a long transmission line. In the detailed machine model, the stator is represented by a dependent current source in parallel with the inductance. Its rotor flux linkage is expressed in terms of currents which are defined wit respect to the machine reference frame. To have a common axis of representation with the network and SVS, these flux linkages are transformed to synchronously rotating D-Q frame of reference.

A SVS auxiliary controller is then developed using Fortran Power Station , which is an advanced software for analyzing and simulating a variety of dynamic systems. The performance is evaluated for enhancement of dynamic stability of a series compensated transmission lines by computing the Eigen value of the linearised system model.

The dynamic performance of the series compensated power system has been evaluated by performing the eigen value analysis .A linearised power system model has been developed and system eigen values have been computed with and without incorporating the combined reactive power and voltage angle SVS auxiliary controller.It is seen that the unstable modes of the system are effectively stabilized and the dynamic performance is greatly improved.

CONTENTS

CHAPTER 1

INTRODUCTION

In recent years, dynamic stability has become one of the most important problems in power system operation. Therefore, significant research efforts have been devoted in developing new analysis tools to cope with this type of stability.

Due to environmental, regulatory and economical constraints, modern power systems are been forced to operate closer to their loadability limits. This has a negative effect on the stability of the system. Hence there is a need to increase the capabilities of transmission lines, the increase in generation near the load centre, the reduction in cyclic peak load requirements, etc. However these methods are either costly or difficult to implement.

FACTS devices are very effective and capable of enhancing the power transfer capability and flexible control of power flow through transmission lines while maintaining stability and reliability of power system [38].

The problem of sub synchronous resonance which threatened the series compensation technology some years back has been successfully tackled using Facts controller like Static Var System (SVS), Thyristor controlled series compensator (TCSC), Static Synchronous series compensator (SSSC).

IEEE has given the definition of FACTS as follows-

"Alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability and increase power transfer capability."

The FACTS technology is not a single high power controller but rather a collection of controllers which can be applied individually or in coordination with other to control one or more of the inter related system parameters like voltage , current , impedance , phase angle and system parameters like voltage , current , impedance , phase angle and damping of oscillations at various frequencies below the rated frequency.

The Facts controllers can be classified according to their connection to the controlled AC Transmission system as-

1. Shunt connected controllers
2. Series connected controllers
3. Combined shunt and series connected controllers
4. Combined series-series controllers.

Static Var System (SVS)

SVS are used to control the voltage profile under load variations, increase power transfer capability and to improve system stability . They can be used for damping power system oscillations incorporating some auxiliary signals. SVC's are first generation FACTS controllers which are expected to revolutionarize power transmission in future. These are also used for power factor compensation of dynamic loads such as steel mills and arc furnaces and load balancing. They can provide better control of power flow on parallel path which is important in relatively tight mesh networks[41].

There are mainly two types of Static VAR Compensator configuration which are used in power system. A continuous control over the capacitive and inductive range of reactive power can be achieved from either of two SVS configurations, FC-TCR or TSC-TCR.[40].

It has been reported by Gyugyi [40] that while the steady state characteristics and response of both the compensators are identical for small voltage perturbations, the operating behavior of TSC-TCR is also characterized by low losses and reduced harmonic contents.

Applications of Static VAR Compensators

By virtue of the ability of SVC to provide continuous and rapid control of reactive power and voltage SVS can enhance many aspects of transmission system performance. Applications to date include the following-

- Control of temporary overvoltages
- Prevention of voltage collapse
- Enhancement of Transient Stability
- Enhancement of damping of system oscillation
- Balancing the unbalanced loads
- Eliminating voltage flicker
- Damping sub-synchronous resonance
- Power factor improvement
- Loss reduction
- Enhancement of power transfer capability

STATCOM, Static Synchronous Compensator belongs to the second generation FACTS controller and is based on voltage source converter using gate turn off thyristors (GTO's) and is presently considered the most practical for high power utility applications. The controller can provide both capacitive and inductive compensation and is able to control output current over the rated maximum capacitive or inductive range independent of AC System voltage. The controller can provide full capacitive output current at any output current with the decreasing system voltage. So STATCOM is more effective than the SVC for voltage improvement and transient stability enhancement.

SSSC, Static Synchronous Series Compensator was proposed by Gyugyi in 1989. It is a Static Synchronous Series generator operated without an external electric energy source as a series compensator whose output voltage is in quardature with and controllable independently of the line current for increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. It is like STATCOM, except the output AC voltage is in series with the line.

Sub synchronous Resonance

The phenomenon of Sub-synchronous resonance (SSR) occurs mainly in series capacitor compensated transmission systems. The first SSR problem was experienced in 1970 resulting in the failure of turbine generator shaft at Mohave plant in Southern California. The following definition of SSR is given in IEEE Committee report (1985).

"Subsynchronous resonance is an electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system.

Outline of the Dissertation

A chapter wise summary of the work done in this dissertation is described below-

Chapter 1 describes the introduction part of the dissertation highlighting the development of the system model for dynamic performance of the system. Study system consists of a generator supplying power to an infinite bus over a long transmission line. In the detailed machine model, the stator is represented by a dependent current source in parallel with the inductance. Its rotor flux linkage is expressed in terms of currents which are defined wit respect to the machine reference frame. To have a common axis of representation with the network and SVS, these flux linkages are transformed to synchronously rotating D-Q frame of reference.

The generator model model includes field winding and a damper winding along q-axis.

The network is represented by using π circuit .The midpoint location of the SVS is chosen with regards to its capability to transfer maximum power over the line.

In chapter 4, a new scheme has been developed for achieving stability in series compensated transmission lines . The scheme utilizes the damping effect of combined reactive power and voltage angle SVS auxiliary controller.

The dynamic performance of the series compensated power system has been evaluated by performing the eigen value analysis .A linearised power system model has been developed and system eigen values have been computed with and without incorporating the combined reactive power and voltage angle SVS auxiliary controller.It is seen that the unstable modes of the system are effectively stabilized and the dynamic performance is greatly improved.

CHAPTER 2

LITERATURE REVIEW

A Detailed literature survey shows that there has been a lot of work done in the field of FACTS controller, specially Static VAR System and there is a great need to improve the reactive power control strategy.

Application of Static Var Systems

The application of SVS in long distance power system has received much attention by researchers in recent years. By virtue of its ability to provide continuous and rapid control of reactive power and voltage, SVS can enhance several aspects of transmission system performance. The work reported in literature in the area of SVS application has been classified as follows-

1. Dynamic performance enhancement
2. Enhancement of Transient stability
3. Damping of Sub synchronous resonance

SVS for Dynamic Performance Enhancement

Static Var System is known to extend the stability limit and improve system damping when connected at the intermediate points of the transmission line.

Nelson Martins and L.T.G Lima [21] presented the work relating to the location of SVC taking into account various factors such as dynamic voltage support, capability of damping electromechanical and sub synchronous oscillations. The proposed algorithm attempted to provide an answer to the problems of finding the best location for the sole purpose of damping electromechanical oscillations.

K.R.Padiyar and R.K.Varma [22] presented work concerned with application of damping torque technique to examine the efficacy of various control signals for reactive power modulation of a midpoint located SVS in enhancing power transfer capability of long transmission line.

A new auxiliary signal designated as computer inter frequency [11] was proposed.

Shun Lee and Chun Chang Liu [23] investigated an output feedback SVC for damping the electromechanical oscillations of synchronous generator. An eigen structure assignment technique was applied to design the controller.Eigen value analysis and time domain simulation under different loading conditions were performed in order to demonstrate the effectiveness of the proposed controller.

E.Lerch etal [24] presented an advanced SVC control for damping power oscillations. The proposed SVC used phase angle signal estimated from the measurement of voltage and power at SVC location. As a result of this method it is possible to increase the power system damping considerably particular in critical situations near to stability limit.

E.Z. Zhou [25] developed a theory to analyze power system damping enhancement by application of SVS based on the well known equal criteria. A discontinuous SVC control approach was proposed in which the change of reactive power output at discrete power points was determined by the power deviation on a transmission line. The author proposed that the SVC control approach and developed theory could be applied to solve practical power system damping problems.

K.Ramar and A.Srinivas[9] developed a linearized model of a single machine infinite bus system with SVC for low frequency oscillation studies.

Norouzi,A.H.and Sharaf,A.M.in their paper on Two control schemes to enhance the dynamic performance of the STATCOM and SSSC have done an in-depth investigation of the dynamic performance of the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC) theoretically and by exact digital simulation. A 24-pulse GTO dc-ac converter model is designed to represent the operation of the STATCOM and SSSC within a power transmission system.
Two major factors of the STATCOM instability are analyzed and a new Automatic Gain Controller (AGC) is proposed to ensure the stable operation of the STATCOM under various load conditions.

Pourbeik, P. and Bostrom, A.Ray, B. present a description of modeling and application studies related to a modern static VAr system (SVS) installation in a utility grid. The SVS incorporates a fully integrated static VAr compensator (SVC) and coordinated, automatically switched capacitor banks using a sophisticated control system. The capacitor banks are switched by individual circuit breakers. Descriptions are provided for the SVC control strategy and various levels of modeling details for the application and design studies performed for this device.

SVS for Transient Performance Enhancement

SVS with some auxiliary signals in addition to voltage feedback is very effective for improving power system dynamic and transient stability. The auxiliary signals may change in active power, reactive power, bus frequency, and rotor speed, phase angle derivative of reactive power and active power and combination of these signals.

Y.Y Hsu etal[28] demonstrated the coordinated applications of PSS and SVC for dynamic stability improvement of a longitudinal power system . An analytical approach was developed for determination of PSS parameters. The effectiveness of the coordinated scheme was demonstrated using time domain simulations.

S.Lefebvre etal [29] presented an SVC model based on modal analysis. The model was integrated in EMTP with minimal interface error and by taking into account initialization.

Rahim[30] etal proposed a coordination of dynamic braking strategy and excitation control to arrest the first swing stability as well as subsequent oscillations in power systems. Computer simulation of multimachine system showed a coordinated application of braking resistor capacitor and excitation energy controls the transients effectively.

A.S.R Murthy etal [31] has an attempted to use deviation of reactive power as auxiliary control signal for SVS. The auxiliary controller parameters were obtained using eigen value analysis and by employing the criterion that the damping factor of the two sensitive eigenvalues was made nearly equal.

Damping of Sub synchronous Resonance in Power System

Sub synchronous resonance in series compensated transmission lines is a phenomenon when the electric network exchanges energy with the turbine generator at one or more of the natural frequencies of the combined system below the power frequency.

Extensive research and development efforts have been developed to the development of effective SSR mitigation measures and to find out the permissible range of series compensation levels

R.M.Hamouda etal[32] assessed the advantage of coordinating SVC and PSS for damping inertial and torsional modes of steam turbine generators.

Shun Lee and Chun-Chang Liu [33] proposed a single input multioutput (SIMO) Static Var Controller for stabilizing torsional oscillations. They suggested that the designed controller could easily be implemented by a multi proportion (MPI) controller using medium pressure turbine speed , two low pressure turbine speed and generator shaft speed as the feedback signals.

Eigen value analysis under a wide range of series compensation and loading conditions, time domain, simulation, FFT Analysis for system behavior were also performed to demonstrate the effectiveness of the proposed controller.

K.R.Padiyar and R.K. Varma [22] presented a conceptually different scheme in which an SVS located at the midpoint of a series compensated transmission line was utilized for the suppression for the torsional oscillations using a composite (CIF) auxiliary control signal. The study however was limited only upto eigen value analysis. The proposed scheme needs to be investigated under transient conditions and over a wide range of power transfer.

CHAPTER 3

MODELLING OF POWER SYSTEMS

3.1 INTRODUCTION

Increasing demand of electrical energy requires increasing transmission capabilities. A variety of factors including financial and environmental concerns constrain the construction of new transmission lines. So the transmission lines get overstressed. There is increased interest in better utilization of available transmission corridors by installing flexible AC transmission system (FACTS) devices. The power transfer in an integrated power system is constrained by transient stability, voltage stability and small signal stability. The FACTS devices can reduce the flow of power in heavily loaded lines, resulting in increase loadability, low system loss, and improved stability of network.

Dynamic stability has been a major problem in power system following the introduction of excitation systems and long transmission lines. The stability of power system had been adversely affected by high rating of machines along transmission lines. In recent years considerable efforts have been placed on the enhancement of dynamic stability of power system. The installation of static VAR system at the intermediate point of transmission line can maintain the voltage deviations within close tolerance and causes enhancement of dynamic stability of system.

An efficient design of SVS controller must consider the appropriate model of system and SVS. The knowledge of adequate system model is essential for predicting the exact system behavior and SVS performance under abnormal conditions. In the literature the SVS and system models reported vary from the

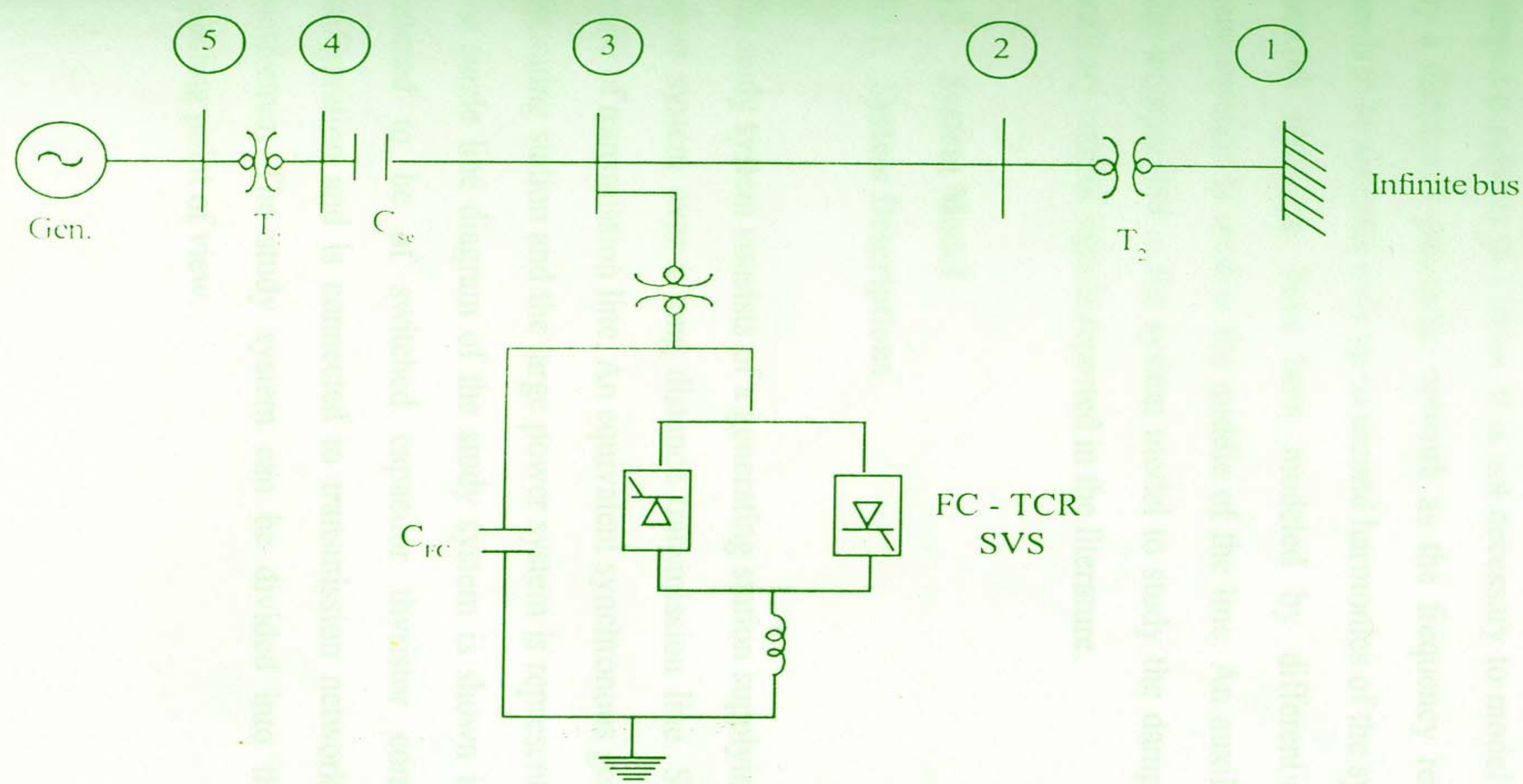


Fig. 3.1 : Study System

most simplistic representation of both AC system and SVS [14,33] to detailed representation of generator, network and SVS .However the higher order system models are useful for assessing the dynamic stability and transient stability.

In the present chapter, a detailed system model is developed for the study system consisting of a generator supplying power to an infinite bus over a long distance transmission line. The SVS is located at the middle of transmission line as this location is found to be most effective as demonstrated in chapter 2.The system model is developed using a network model represented by lumped parameter pi Circuit. It is not necessary to model the transmission line by a distributed parameter network as the frequency response of the model needs to be accurate only up to second harmonics of the system frequency. The network transients have been modeled by differential equations. Series compensation is used in the middle of the line. An auxiliary control signal is also incorporated in the system model to study the damping effect of various auxiliary control signals reported in the literature.

3.2 System Model

3.2.1 System Descriptions

The study system consists of a generating station supplying bulk power a large power system over a long distance transmission line. SVS is located at the center of transmission line. An equivalent synchronous generator represents the generating station and the large power system is represented as an infinite bus. The single line diagram of the study system is shown in fig 3.1 the SVS is assumed to be of switched capacitor thyristor controlled reactor type configuration and is connected to transmission network through a coupling transformer. The study system can be divided into three sub-systems for modeling point of view.

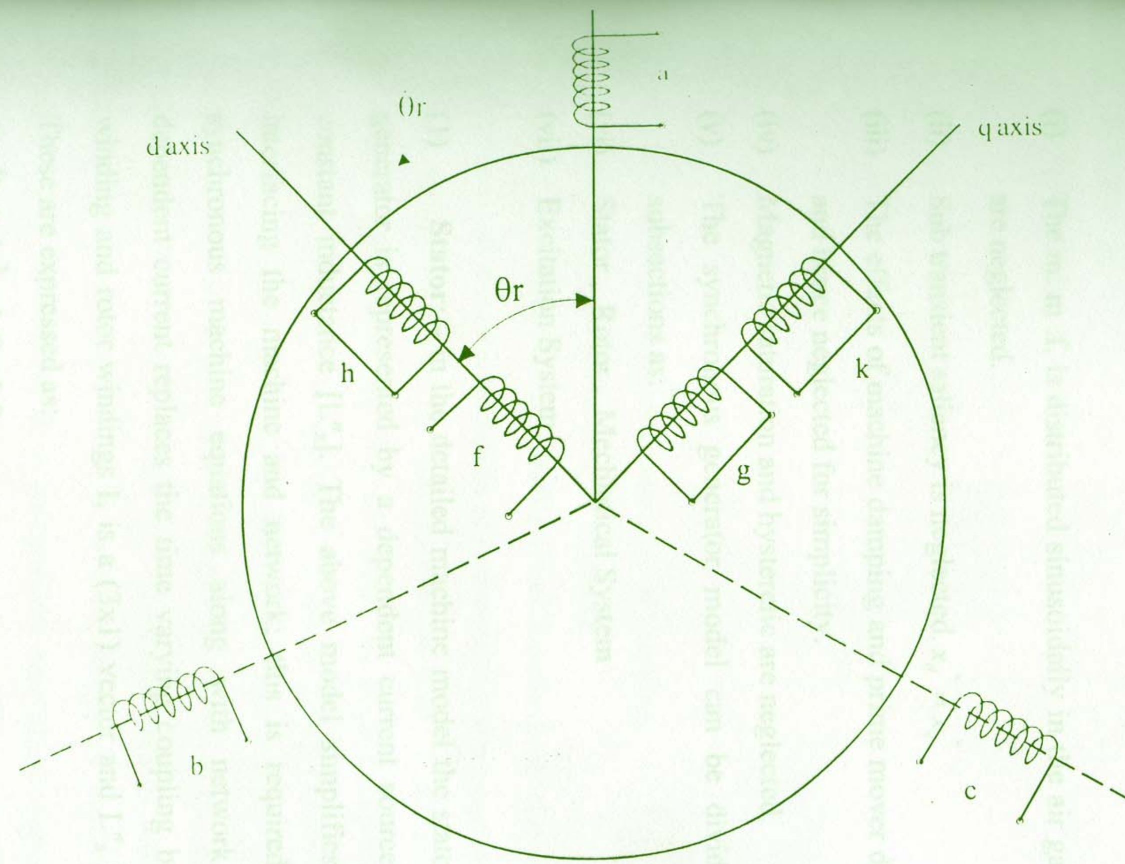


Fig. 3.2: Schematic layout of windings of Synchronous Machine and Their Two Axis Representation

3.2.2 Generator Model

The detailed mathematical model of synchronous generator used here (12) is in such form which can be directly utilized for dynamic stability analysis and system simulation. The synchronous generator is represented by three symmetrically placed armature winding a, b, c, one field winding f and three damper winding h, g, k, (fig. 3.2). The damper windings are considered to model the eddy current effects in a solid rotor machine. The following assumptions are used in deriving the basic equations of the machine.

(i) The m. m .f. is distributed sinusoidally in the air gap and harmonics are neglected.

(ii) Sub transient saliency is neglected. $x_d'' = x_q''$

(iii) The effects of machine damping and prime mover dynamic are small and hence neglected for simplicity.

(iv) Magnetic saturation and hysteretic are neglected.

(v) The synchronous generator model can be divided in following subsections as:

(vi) Stator , Rotor , Mechanical System

(vii) Excitation System

(1) **Stator: -** in the detailed machine model the stator of synchronous generator is represented by a dependent current source in parallel with constant inductance [L''_s]. The above model simplifies the problem of interfacing the machine and network; this is required for solution of synchronous machine equations along with network equations. The dependent current replaces the time varying coupling between the stator winding and rotor windings I_s is a (3x1) vector and L''_s is a (3x3) matrix. These are expressed as:

$$I_s = [I_a \ I_b \ I_c]^t = I_d C + I_q S \qquad (3.1)$$

Where

$$C^t = \sqrt{\frac{2}{3}}\left[\cos\theta \quad \cos\left(\theta - \frac{2\pi}{3}\right) \quad \cos\left(\theta + \frac{2\pi}{3}\right)\right]$$

$$S^t = \sqrt{\frac{2}{3}}\left[\sin\theta \quad \sin\left(\theta - \frac{2\pi}{3}\right) \quad \sin\left(\theta + \frac{2\pi}{3}\right)\right]$$

$$I_d = C_1 \psi_f + C_2 \psi_h$$

$$I_q = C_3 \psi_g + C_4 \psi_k + C_5 \psi_c$$

I_d and I_q are the component of dependant current source along d and q axis receptively.

θ = rotor angle

The constants C_1- C_4 are given in appendix A_1

$$L''s = \frac{L_0}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} + \frac{2L_d''}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix} \qquad (3.2)$$

Where L''_d= Sub-transient inductance of machine.

L_0 = zero sequence inductance of machine.

Such a representation of machine can handle both the external network connected to machine terminals is symmetrical, as considered in this case a, b, c, components can be transformed to α, β, o components by using Clarke's transformation. All the three α, β, o component models are uncoupled. Equivalent source representation of machine (12) on α, β, o axis is shown in fig. (3.4), the relationship between α, β, o components and phase current i_a, i_b, i_c is given by

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{3} & 0 & \frac{1}{\sqrt{3}} \\ -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} \mathrm{i}_\alpha \\ \mathrm{i}_\beta \\ \mathrm{i}_o \end{bmatrix} \tag{3.3}$$

The dependent current sources in α, β, o frame to reference are defined as

$$\mathrm{i}_\alpha = \mathrm{I_d} \cos\theta + \mathrm{I_q} \sin\theta \tag{3.4}$$

$$i_\beta = -\mathrm{I_d} \sin\theta + \mathrm{I_q} \cos\theta \tag{3.5}$$

$$i_o = o$$

The α -axis equivalent representation of the machine stator current can be directly combined with α -network of the AC transmission system.

(b) Rotor

The rotor flux linkages are defined as follows:

$$\Psi_f = \mathrm{a_1}\psi_\mathrm{f} + \mathrm{a_2}\psi_\mathrm{h} + \mathrm{b_1}\,\mathrm{v_f} + \mathrm{b_2}\,\mathrm{i_d}$$

$$\Psi_h = \mathrm{a_3}\psi_\mathrm{f} + \mathrm{a_4}\psi_\mathrm{h} + \mathrm{b_3}\,\mathrm{i_d}$$

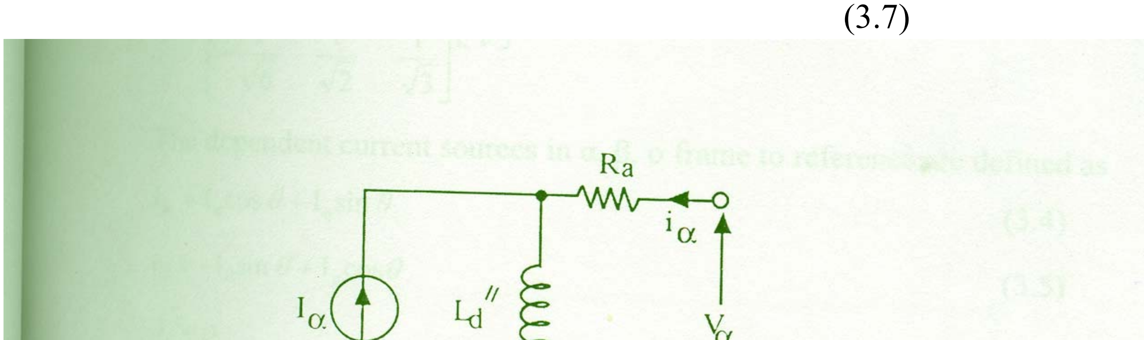
$$\Psi_g = \mathrm{a_5}\psi_\mathrm{g} + \mathrm{a_6}\psi_\mathrm{k} + \mathrm{b_5}\,\mathrm{i_q}$$

$$\Psi_k = \mathrm{a_7}\psi_\mathrm{g} + \mathrm{a_8}\psi_\mathrm{h} + \mathrm{b_6}\,\mathrm{i_q} \tag{3.6}$$

Where V_f is field excitation voltage.

Constants a_1 to a_8 and b_1 to b_6 are defined in appendix A_1, i_d, and i_q are the d-axis and q-axis, component of the machine terminals current and are defined by

$$i_d = \frac{\sqrt{2}}{3}\left[i_a \cos\theta + i_b \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \cos\left(\theta + \frac{2\pi}{3}\right)\right] \tag{3.7}$$



$$i_q = \frac{\sqrt{2}}{3}\left[i_a \sin\theta + i_b \sin\left(\theta - \frac{2\pi}{3}\right) + i_c \sin\left(\theta + \frac{2\pi}{3}\right)\right]$$

(3.8)

It is noted that currents i_d and i_q are defined w. r. t. machine reference frame. These currents are transformed to D-Q frame of reference to have common axis of representation with the AC network and SVS, which is rotating at synchronous speed ω_o. The following transforming is employed.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} i_D \\ i_Q \end{bmatrix} \qquad (3.9)$$

Where i_D, i_Q, are the components of the machine current along D-axis and Q-axis respectively. Substituting eqn (3.9) in eqn (3.6) and linearizing the resultant equations, we have the state equation of the rotor circuit as following

$$\begin{bmatrix} \Delta\dot{\Psi}_f \\ \Delta\dot{\Psi}_h \\ \Delta\dot{\Psi}_g \\ \Delta\dot{\Psi}_h \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & 0 & 0 \\ a_3 & a_4 & 0 & 0 \\ 0 & 0 & a_5 & a_6 \\ 0 & 0 & a_7 & a_8 \end{bmatrix} \begin{bmatrix} \Psi_f \\ \Psi_h \\ \Psi_g \\ \Psi_k \end{bmatrix} + \begin{bmatrix} -b_2 i_{qo} & 0 \\ -b_3 i_{qo} & 0 \\ b_5 i_{qo} & 0 \\ b_6 i_{qo} & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} b_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \left[\Delta V_f\right] + \begin{bmatrix} b_2\cos\delta & -b_2\sin\delta \\ b_3\cos\delta & -b_3\sin\delta \\ b_5\cos\delta & b_5\cos\delta \\ b_6\cos\delta & b_6\cos\delta \end{bmatrix} \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix}$$

or $\dot{X}_R = [A_R] X_R + [B_{R1}] U_{R1} + [B_{R2}] U_{R2} + [B_{R3}] U_{R3}$ (3.10)

Where $X_R = \left[\Delta\psi_f \Delta\psi_h \ \Delta\psi_g \ \Delta\psi_k\right]^t$

$u_{R1} = [\Delta\delta \quad \Delta\omega]^t, u_{R2} = [\Delta v_f]^t, U_{R3} = [\Delta i_D \quad \Delta i_Q]^t$

Using the relationship between I_d, I_q, and rotor fluxes linkage develops the out put equations of rotor circuit. (12)

$I_d = C_1\psi_f + C_2\psi_h$

$I_q = C_3\psi_g + C_4\psi_k$

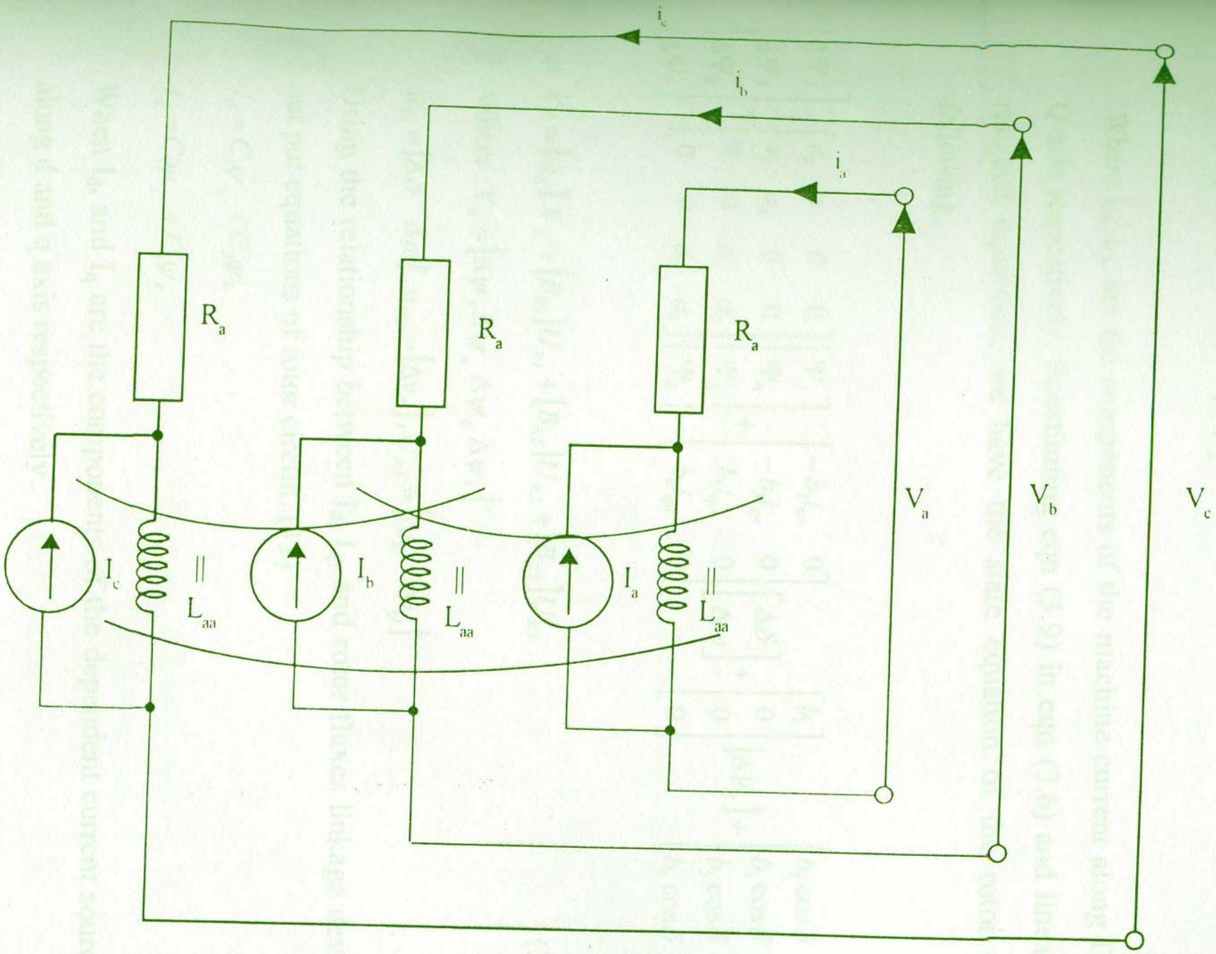


Fig.3.4: Circuit model for the stator of Synchronous Machine

When I_d, and I_q are the components of the dependent current source shown along d and q axis respectively.

$$C_1 = \frac{X_{df}\, x_h - x_{dh}\, x_{fh}}{X_d''\left[x_f\, x_h' - x^2{}_{fh}\right]},\quad C_2 = \frac{X_{dh}\, X_f - x_{fh}\, x_{df}}{x_d''\left[x_f x_h - x^2{}_{fh}\right]}$$

$$C_3 = \frac{X_{qg}\, X_k - X_{qk}\, X_{gk}}{X''_d\left(X_g X_k - X^2{}_{qk}\right)},\quad C_4 = \frac{X_{qk}\, X_g - X_{gk}\, X_{qg}}{X_d''\left(X_g X_k - X^2{}_{gk}\right)} \qquad (3.11)$$

By kron's transformation

$$\begin{bmatrix} I_D \\ I_Q \end{bmatrix} = \begin{bmatrix} cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \qquad (3.12)$$

Or $I_D = (c_1\, \psi_f + c_2\, \psi_h) \cos\delta + (c_3\psi_g + c\psi_k) \sin\delta$

And $I_Q = -(c_1\psi_f + c_2\psi_h) \sin\delta + (c_3\psi_g + c_4\psi_k) \cos\delta$

Linear zing Eqn. ,we get

$$\begin{bmatrix} \Delta I_D \\ \Delta I_Q \end{bmatrix} = \begin{bmatrix} C_1 cos\delta & C_2\cos\delta & C_3\sin\delta & C_4\sin\delta \\ -C_1\sin\delta & -C_2\sin\delta & C_3\cos\delta & C_4\cos\delta \end{bmatrix} \begin{bmatrix} \Delta\psi_f \\ \Delta\psi_h \\ \Delta\psi_g \\ \Delta\psi_k \end{bmatrix} + \begin{bmatrix} I_{Q0} & 0 \\ -I_{D0} & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta w \end{bmatrix} \qquad (3.13)$$

or $Y_{R1} = [C_{R1}]\, X_R + [D_{R1}] U_{R1}$ (3.14)

By differentiating and linearizing Eqn. (3.13)

$$\begin{bmatrix} \Delta \dot{I}_D \\ \Delta \dot{I}_Q \end{bmatrix} = \begin{bmatrix} (C_1 a_1 + C_2 a_3) \cos\delta & (C_1 a_2 + C_2 a_4) \cos\delta & (C_3 a_5 + C_4 a_7) \sin\delta & (C_3 a_6 + C_4 a_8) \sin\delta \\ -(C_1 a_1 + C_2 a_2) \sin\delta & -(C_1 a_3 + C_2 a_4) \sin\delta & (C_3 a_5 + C_4 a_7) \cos\delta & (C_3 a_6 + C_4 a_8) \cos\delta \end{bmatrix}$$

$$x \begin{bmatrix} \Delta\psi_f \\ \Delta\psi_h \\ \Delta\psi_g \\ \Delta\psi_k \end{bmatrix} + \begin{bmatrix} -(C_1 b_2 + C_2 b_3)\, id_0 \cos\delta_0 + (C_3 b_5 + C_4 b_5) id_0 \sin\delta_0 & I_{Q_0} \\ (C_1 b_2 + C_2 b_3) iq_0 \sin\delta_0 + (C_3 b_5 + C_4 b_6) id_0 \cos\delta_0 & -I_{D_0} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix}$$

$$+ \begin{bmatrix} C_1 b_1 \cos\delta_0 \\ -C_1 b_1 \sin\delta_0 \end{bmatrix} [\Delta V_f]$$

$$+\begin{bmatrix} (C_1b_2+C_2b_3)cos^2\delta_0 & -(C_1b_2+C_2b_3)sin\,\delta_0\,cos\,\delta_0 \\ +(C_3b_5+C_4b_6)sin^2\delta_0 & +(C_3b_5+C_4b_6)sin\,\delta_0\,cos\delta_0 \\ -(C_1b_2+C_2b_3)sin\delta_0\,cos\delta_0 & (C_1b_2+C_2b_3)sin^2\delta_0 \\ +(C_3b_5+C_4b_6)sin\delta_0\,cos\delta_0 & +(C_3b_5+C_4b_6)cos^2\delta_0 \end{bmatrix}\begin{bmatrix}\Delta I_D \\ \\ \\ \Delta I_Q\end{bmatrix}$$

Where $i_{d0} = i_{D0}\,cos\,\delta_0 - i_{Q0}\,sin\delta_0$

$i_{q0} = i_{D0}\,sin\,\delta_0 - i_{D0}\,cos\,\delta_0$

$I_{D0} = (C_1\psi_f + C_2\psi_h)cos\,\delta_0 + (C_3\psi_g + C_4\psi_k)sin\,\delta_0$

$I_{QO} = -(C_1\psi_f + C_2\psi_h)sin\,\delta_0 + (C_3\psi_g + C_4\psi_k)cos\delta_0$

Or $Y_{R2} = [C_{R2}]\, X_R + [D_{R2}]\, U_{R1} + [D_{R3}]\, U_{R2} + [D_{R4}]\, U_{R3}$ (3.15)

3.2.3 Mechanical System

The rotor of a turbine generator unit is a complex mechanical system made up of several rotors of different size, each with the system mechanical shaft section and couplings. The mechanical system can be described using either the multi resonant mechanical model (all modes model) or the model mechanical model.

The rotor angle is expressed as

$\theta = \theta_r + \delta$

where , $\theta_r = \omega_0 t$

The nominal system frequency ω_0 is given by

$\omega_0 = d\,\theta_r / d\,t$

Differentiating above equation and substituting

$d\theta/ dt = d\,\theta_r / d\,t + d\delta/ d\,t$

or $\omega = \omega_0 + d\delta/ d\,t$

or $d\delta/ d\,t = \omega = \omega_0$

The machine swing equation is given by

$$d\omega / dt = \omega_0/2H\,(-D\,\omega + T_m - T_e)$$

where ,

H = inertia constant of the generator

D = damping torque coefficient

T_m = mechanical torque

T_e = electrical torque

The electromagnetic torque T_e is given by

$$T_e = -X_d''\,(i_d\, I_q - i_q\, I_d)$$

Substituting the above equation

$$d\omega / dt = \omega_0/2H\,[-D\,\omega + T_m + X_d''\,(i_d\, I_q - i_q\, I_d)]$$

i_d , i_q and I_d , I_q are transformed to D-Q frame of reference using the above relationship

$$d\omega / dt = \omega_0/2H\,[-D\,\omega + T_m + X_d''\,(i_D\, I_Q - i_Q\, I_D)]$$

Linearizing the two equations and writing in matrix form

$$\begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -D\,\omega_0/2H \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} & \\ \dfrac{-\omega_0 X_d''\, i_{Q0}}{2H} & \dfrac{-\omega_0 X_d''\, i_{Q0}}{2H} \end{bmatrix} \begin{bmatrix} \\ \\ \end{bmatrix}$$

$$+ \begin{bmatrix} 0 & 0 \\ \dfrac{-\omega_0 X_d''\, I_{Q0}}{2H} & \dfrac{-\omega_0 X_d''\, I_{D0}}{2H} \end{bmatrix} \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix}$$

where

$$X_d'' = -\omega_0 L_d''$$

$$X_M = \begin{bmatrix} A_M \end{bmatrix} X_M + \begin{bmatrix} B_{M1} \end{bmatrix} U_{M1} + \begin{bmatrix} B_{M2} \end{bmatrix} U_{M2}$$

$$X_M = \left[\Delta\delta , \Delta\omega\right]^t , \quad U_{M1} = \left[\Delta I_D \;\; \Delta I_Q\right]^t, \; UM2 = \left[\Delta i_D \;\; \Delta i_Q\right]^t$$

The output equation of the mechanical system is given by

$$\begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix}$$

3.2.4 Excitation System

The excitation system is described by the following equations:

$$\dot{V}_f = -\frac{(K_E + S_E)}{T_E} V_f + \frac{1}{T_E} V_r$$

$$\dot{V}_s = -\frac{K_F (K_E + S_E)}{T_E T_F} V_f - \frac{1}{T_F} V_S + \frac{K_F}{T_E T_F} V_r \tag{3.30}$$

$$\dot{V}_r = -\frac{K_A}{T_A} V_S - \frac{1}{T_A} V_r - \frac{K_A}{T_A} V_g + \frac{K_A}{T_A} V_{REF}$$

The state and out put equations of the linealized system are

$$\begin{bmatrix} \Delta\dot{V} f \\ \Delta\dot{V} s \\ \Delta\dot{V} r \end{bmatrix} = \begin{bmatrix} -\frac{(K_E + S_E)}{T_E} & 0 & \frac{1}{T_E} \\ \frac{-K_F (K_E + S_E)}{T_E T_F} & -\frac{1}{T_F} & \frac{K_F}{T_E T_F} \\ 0 & \frac{-K_A}{T_A} & -\frac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta V_f \\ \Delta V_s \\ \Delta V_r \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{-K_A}{T_A} \end{bmatrix}$$

or $\dot{X}_E = [A_E] X_E + [B_E] U_E$ (3.31)

The out put equation in given by

$$[\Delta V_f] = [1 \;\; 0 \;\; 0] \begin{bmatrix} \Delta V_f \\ \Delta V_s \\ \Delta V_r \end{bmatrix}$$

or $Y_E = [C_E] X_E$ (3.32)

Where $X_E = [\Delta V_f \;\; \Delta V_s \;\; \Delta V_r]^t$, $U_E = \Delta V_g$, $Y_E = \Delta V_f$

Network Model:

The transmission line is represented by a single lumped π circuit shown in fig (3.7). The charging capacitance of the line is combined with fixed capacitor of the SVS the equivalent circuit of the stator of the synchronous machine is also included in the network model. It is assumed that network components are symmetrical. Hence the network has been represented by its α-axis equivalent circuit, which is identical with the positive sequence network, the generator transformer and receiving end transformer are represented by their leakage inductance. The magnetizing current in neglected. The shunt conductance of the line is also neglected.

I_α is the α-axis component of dependant current source as described in the stator circuit model of synchronous machine. Series compensation is provided at the centre of the line towards the line side of transformer. The current entering the infinite bus, SVS and generator as represented by $i_{1\alpha}$ $i_{2\alpha}$ $i_{3\alpha}$ respectively. The corresponding terminal voltages are indicated by $V_{1\alpha}$, $V_{2\alpha}$ and $V_{g\alpha}$. R, L represents the series resistance and inductance of half line section. L_{T1} and L_{T2} are the leakage inductances of the transformers at the sending end receiving end. At the SVS bus, C_n represent the sum of line charging capacitance of the two line sections and SVS fixed capacitor.

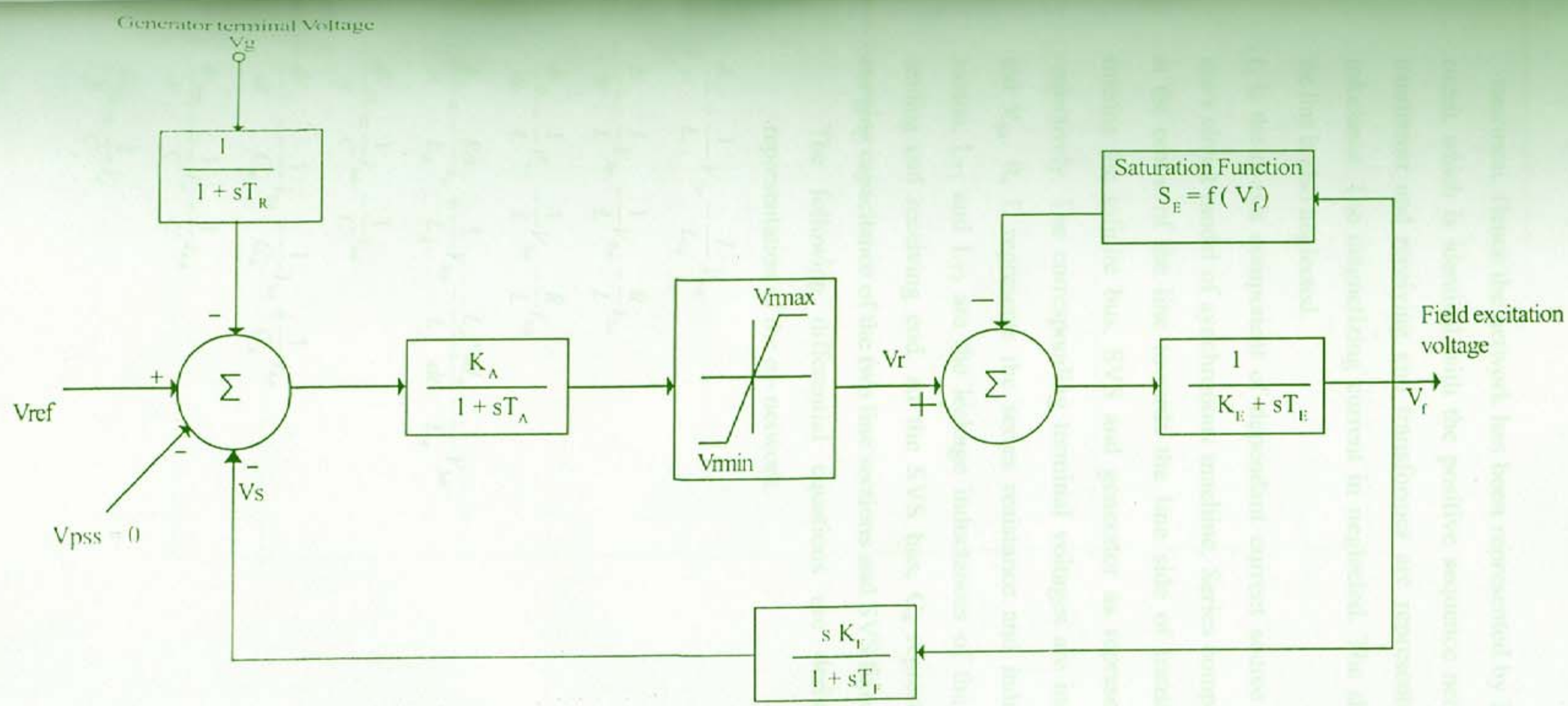


Fig. 3.6 : Block Diagram of IEEE Type - 1 Excitation system

The following differential equations are derived for the circuit representation of the α - network.

$$\frac{di_{1\alpha}}{dt} = \frac{1}{L_{T2}}V_{2\alpha} - \frac{1}{L_{T2}}V_{1\alpha} \tag{3.33}$$

$$\frac{di_{2\alpha}}{dt} = \frac{1}{L}V_{3\alpha} - \frac{1}{L}V_{2\alpha} - \frac{R}{L}i_{2\alpha} \tag{3.34}$$

$$\frac{di_{4\alpha}}{dt} = \frac{1}{L}V_{4\alpha} - \frac{1}{L}V_{3\alpha} - \frac{R}{L}i_{4\alpha} \tag{3.35}$$

$$\frac{di_{\alpha}}{dt} = -\frac{Ra}{L_A}i_{\alpha} + \frac{1}{L_A}V_{4\alpha} - \frac{L_d"}{L_A}\frac{dI_{\alpha}}{dt} - \frac{1}{L_A}V_{5\alpha} \tag{3.36}$$

$$\frac{dV_{2\alpha}}{dt} = \frac{1}{C}i_{2\alpha} - \frac{1}{C}i_{1\alpha} \tag{3.37}$$

$$\frac{dV_{3\alpha}}{dt} = -\frac{1}{C_n}i_{2\alpha} - \frac{1}{C_n}i_{3\alpha} + \frac{1}{C_n}i_{4\alpha} \tag{3.38}$$

$$\frac{dv_{4\alpha}}{dt} = -\frac{1}{C}i_{\alpha} - \frac{1}{C}i_{4\alpha} \tag{3.39}$$

$$\frac{dv_{6\alpha}}{dt} = \frac{1}{C_{se}}i_{\alpha} \tag{3.40}$$

Where $C_n = C_T + C_{FC}$, $L_A = L_{T1} + L_d$", $L_1 = L + L_A$

$L_2 = L + L_{T2}$ and $R_1 = R + R_a$

Similarly the equations can be derived for β network

The equations of α - β network are transformed to synchronous rotating D-Q frame of reference using Kron's transformation and are subsequently linearized since the infinite bus voltage is constant $\Delta V_{1D} = \Delta V_{1Q}$=O

The linearized state equation of the network model is finally obtained as follows:

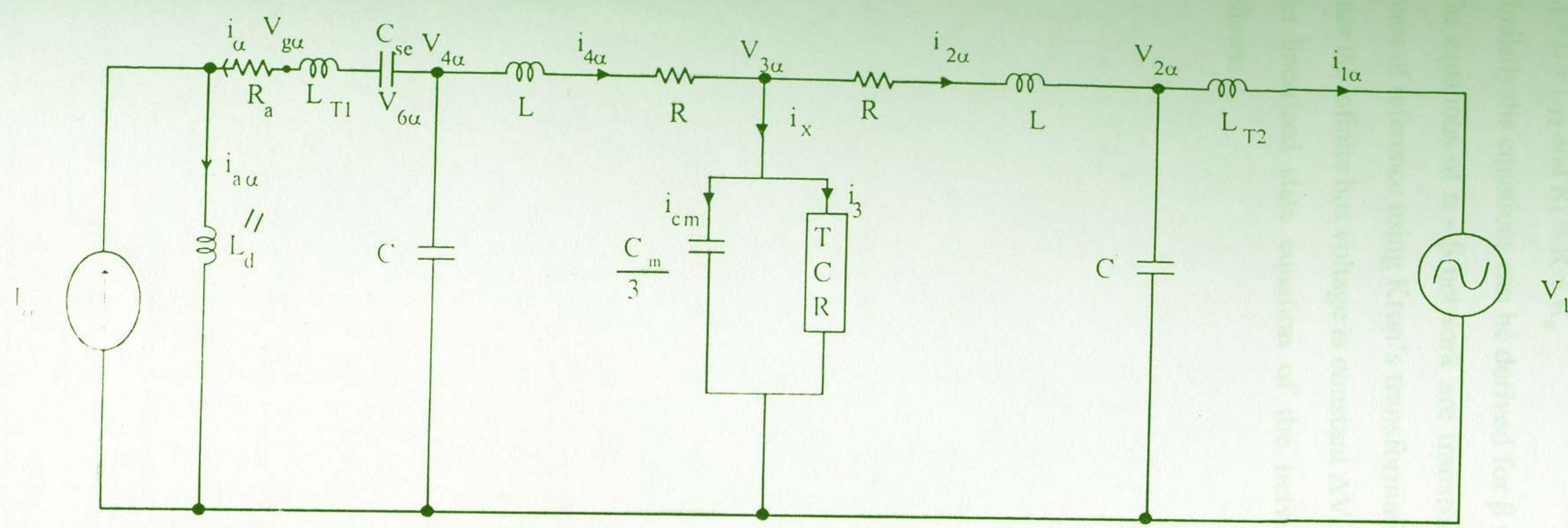


Fig.3.7 : α - Axis Representation of Series Compensated Network (π - Circuit Representation)

$$
\begin{bmatrix} \Delta \dot{i}_{1D} \\ \Delta \dot{i}_{2D} \\ \Delta \dot{i}_{4D} \\ \Delta \dot{i}_{D} \\ \Delta \dot{V}_{2D} \\ \Delta \dot{V}_{3D} \\ \Delta \dot{V}_{4D} \\ \Delta \dot{V}_{5D} \\ \Delta \dot{i}_{1Q} \\ \Delta \dot{i}_{2Q} \\ \Delta \dot{i}_{4Q} \\ \Delta \dot{i}_{Q} \\ \Delta \dot{V}_{2Q} \\ \Delta \dot{V}_{3Q} \\ \Delta \dot{V}_{4Q} \\ \Delta \dot{V}_{5Q} \end{bmatrix}
=
\begin{bmatrix}
0 & -\frac{R}{L} & 0 & 0 & -\frac{1}{L} & \frac{1}{L} & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{R}{L} & 0 & 0 & -\frac{1}{L} & \frac{1}{L} & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\frac{R_a}{L_A} & 0 & 0 & \frac{1}{L_A} & -\frac{1}{L_A} & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 \\
-\frac{1}{C} & \frac{1}{C} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 \\
0 & -\frac{1}{C_n} & \frac{1}{C_n} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 \\
0 & 0 & -\frac{1}{C} & -\frac{1}{C_n} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 \\
0 & 0 & 0 & \frac{1}{C_{se}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 \\
\omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{T2}} & 0 & 0 & 0 \\
0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R}{L} & 0 & 0 & -\frac{1}{L} & \frac{1}{L} & 0 & 0 \\
0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R}{L} & 0 & 0 & -\frac{1}{L} & \frac{1}{L} & 0 \\
0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{R_a}{L_A} & 0 & 0 & \frac{1}{L_A} & -\frac{1}{L_A} \\
0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & -\frac{1}{C} & \frac{1}{C} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & -\frac{1}{C_n} & \frac{1}{C_n} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & \frac{1}{C} & -\frac{1}{C} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & \frac{1}{C_{se}} & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} \Delta i_{1D} \\ \Delta i_{2D} \\ \Delta i_{4D} \\ \Delta i_{D} \\ \Delta V_{2D} \\ \Delta V_{3D} \\ \Delta V_{4D} \\ \Delta V_{6D} \\ \Delta i_{1Q} \\ \Delta i_{2Q} \\ \Delta i_{4Q} \\ \Delta i_{Q} \\ \Delta V_{2Q} \\ \Delta V_{3Q} \\ \Delta V_{4Q} \\ \Delta V_{5Q} \end{bmatrix}
$$

$$
+\begin{bmatrix}
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
-\frac{1}{C_n} & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & -\frac{1}{C_n}\\
0 & 0\\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta i_{3D}\\
\Delta i_{3Q}
\end{bmatrix}
+\begin{bmatrix}
0 & 0\\
0 & 0\\
0 & 0\\
-\omega o\frac{L_d''}{L_A} & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & -\omega o\frac{L_d''}{L_A}\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \dot{I}_D\\
\Delta I_Q
\end{bmatrix}
$$

$$
+\begin{bmatrix}
0 & 0\\
0 & 0\\
0 & 0\\
-\frac{L_d''}{L_A} & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & -\frac{L_d''}{L_A}\\
0 & 0\\
0 & 0\\
0 & 0\\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \dot{I}_D\\
\Delta \dot{I}_Q
\end{bmatrix}
$$

or $X_N = [A_N]X_N + [B_{N1}]\,U_{N1} + [B_{N2}]\,U_{N2} + [B_{N3}]U_{N3}$

The output variables of the network model are the voltage and current at the generator terminals and the SVS but voltage. The generator terminals voltage for the α -network is given by

$V_{g\alpha} = R_a i_{\alpha} + L_d'' (i_\alpha + I_\alpha)$ (3.41)

Similarly the equation can be written for the β network

$V_{g\beta} = R_a i_{\beta} + L_d'' (i_\beta + I_\beta)$ (3.42)

Transforming the above equations to the synchronous rotating D-Q frame of reference

$$V_{gD} = R_a i_D + L''_d (i_D + I_D) + \omega_o L''_d (i_q + I_Q) \tag{3.43}$$

$$V_{gQ} = R_a i_Q + L''_d (i_Q + I_Q) - \omega_o L'' d (i_D + I_D) \tag{3.44}$$

Linearizing eqns. (3.41) and (3.42) the network out put equations can be obtained as:

$$\begin{bmatrix} \Delta V_{gD} \\ \Delta V_{gQ} \end{bmatrix} = \left[\begin{matrix} 0 & -R_a(1-\frac{L_d''}{L_A}) & 0 & 0 & 0 & 0 & \frac{L_d''}{L_A} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega C_n R_a\left(1-\frac{L_d''}{L_A}\right) & -\omega C_n R_a\left(1-\frac{L_d''}{L_A}\right) & 0 \end{matrix}\right.$$

$$\left.\begin{matrix} 0 & 0 & 0 & 0 & 0 & \omega C_n R_a\left(1-\frac{L_d''}{L_A}\right) & \omega C R_a\left(1-\frac{L_d''}{L_A}\right) & 0 \\ 0 & -R_a\left(1-\frac{L_d''}{L_A}\right) & 0 & 0 & 0 & 0 & \frac{L_d''}{L_A} & 0 \end{matrix}\right]$$

$$+\begin{bmatrix} -R_a\left(1-\frac{L_d''}{L_A}\right) & 0 \\ 0 & -R_a\left(1-\frac{L_d''}{L_A}\right) \end{bmatrix} \begin{bmatrix} \Delta i_{3D} \\ \Delta i_{3Q} \end{bmatrix} + \begin{bmatrix} 0 & \omega_o L_d'' - \omega_o \frac{L_d''^2}{L_A} \\ -\left(\omega_o L_d'' + \frac{\omega_o L_d''^2}{L_A}\right) & 0 \end{bmatrix} \begin{bmatrix} \Delta I_D \\ \Delta I_Q \end{bmatrix} +$$

$$+\begin{bmatrix} \left(L_d'' - \frac{L_d''^2}{L_A}\right) & 0 \\ 0 & \left(L_d'' - \frac{L_d''}{L_A}\right) \end{bmatrix} \begin{bmatrix} \Delta \dot{I}_D \\ \Delta \dot{I}_Q \end{bmatrix}$$

or $Y_{N1} = [C_{N1}][X_N]+ [D_{N1}]U_{N1} + [D_{N2}]U_{N2} + [D_{N3}]U_{N3}$ (3.45)

The output equations in terms of generator terminals currents will be as follows:

$$\begin{bmatrix} \Delta \dot{i}_D \\ \Delta \dot{i}_Q \end{bmatrix} = \begin{bmatrix} 0 & 0\ 0 & 1\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0 \\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 1\ 0 & 0\ 0 & 0 \end{bmatrix} [X_N]$$

or $Y_{N2} = [C_{N2}]X_N$ (3.46)

The output equation in terms of the SVS bus voltage is given by:

$$\begin{bmatrix} \Delta V_{3D} \\ \Delta V_{3Q} \end{bmatrix} = \begin{bmatrix} 0 & 0\ 0 & 0\ 0 & 1\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0 \\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 0\ 0 & 1\ 0 & 0 \end{bmatrix} [X_N]$$

or $Y_{N3} = [C_{N3}]\ [X_N]$ (3.47)

where,

$$Y_{N1} = [\Delta V_{gD} \quad \Delta V_{gQ}]^t,\ YN2 = [\Delta i_D \quad \Delta i_Q]^t,\ Y_{N3} = [\Delta V_{3D} \quad \Delta V_{3Q}]^t$$

$$X_N = [\Delta i_{1D} \quad \Delta i_{2D} \quad \Delta i_{4D} \quad \Delta i_{iD} \quad \Delta V_{2D} \quad \Delta V_{3D} \quad \Delta V_{4D} \quad \Delta V_{6D}$$

$$\Delta i_{1Q} \quad \Delta i_{2Q} \quad \Delta i_{4Q}\ \Delta i_Q \quad \Delta V_{2Q} \quad \Delta V_{3Q}\ \Delta \quad \Delta V_{6Q}]^t$$

$$U_{N1} = [\Delta i_{3D} \quad \Delta i_{3Q}]^t \quad , U_{N2} = [\Delta I_D \quad \Delta I_Q]^t, \quad U_{N3} = \begin{bmatrix} \Delta \dot{I}_D & \Delta \dot{I}_Q \end{bmatrix}^t$$

Static VAR system Model

The linearized model of SVS fig. (3.8) control system is considered here for dynamic performance study. The voltage regulator is assumed to be proportional plus integral (PI) controller. The salient feature of this representation is the modeling of TCR transients. The delays associated with the SVS controller and measurement unit are also incorporated. The α ,β axis currents entering TCR from network are expressed as:

$$L_S \frac{di_{3\alpha}}{dt} + R_S\, i_{3\alpha} = V_{3\alpha} \quad (3.48)$$

$$L_S \frac{di_{3\beta}}{dt} + R_S\, i_{3\beta} = V_{3\beta} \quad (3.49)$$

Where Ls, Rs represent inductance and resistance of TCR respectively. By applying Kron's transformation to eqn. (3.48)

$$\omega_0 L_S i_{3Q} + L_S \dot{i}_{3D} + R_S i_{3D} = V_{3D} \qquad (3.50)$$

or $$\dot{i}_{3D} = \frac{1}{L_S} V_{3D} - \frac{R_S}{L_S} i_{3D} - \omega_0 i_{3Q} \qquad (3.51)$$

Similarly

$$\dot{i}_{3Q} = \frac{1}{L_S} V_{3Q} - \frac{R_S}{L_S} i_{3Q} + \omega_0 i_{3D} \qquad (3.52)$$

Eqns. (3.51) & (3.52) can be rewritten as

$$\dot{i}_{3D} = \omega_0 B V_{3D} - \frac{\omega_0}{Q} i_{3D} - i_{3Q} \qquad (3.53)$$

$$\dot{i}_{3Q} = \omega_0 B V_{3Q} - \frac{\omega_0}{Q} i_{3Q} + i_{3D} \qquad (3.54)$$

Where, $Q = Quality\ Factor = \frac{\omega_0 L_S}{R}$

And $B = \frac{1}{\omega_0 L_S}$

Linearizing (3.53) and (3.54) gives

$$\Delta \dot{i}_{3D} = \omega_0 B_0 \Delta V_{3D} + \omega_0 \Delta B V_{3D0} - \frac{\omega_0}{Q} \Delta i_{3D} - \omega_0 \Delta i_{3Q} \qquad (3.55)$$

$$\Delta \dot{i}_{3Q} = \omega_0 B_0 \Delta V_{3Q} + \omega_0 \Delta B V_{3Q0} - \frac{\omega_0}{Q} \Delta i_{3Q} + \omega_0 \Delta i_{3D} \qquad (3.56)$$

Eqns (3.55) and (3.56) can be written in matrix forms

$$\begin{bmatrix} \Delta \dot{i}_{3D} \\ \Delta \dot{i}_{3Q} \end{bmatrix} = \omega_0 \begin{bmatrix} -\frac{1}{Q} & -1 \\ 1 & -\frac{1}{Q} \end{bmatrix} \begin{bmatrix} \Delta i_{3Q} \\ \Delta i_{3Q} \end{bmatrix}$$

$$+ \omega_0 B_0 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta V_{3D} \\ \Delta V_{3Q} \end{bmatrix} + \omega_0 \begin{bmatrix} \Delta V_{3D0} \\ \Delta V_{3Q0} \end{bmatrix} \Delta B \qquad (3.57)$$

$$\dot{Z}_1 = \Delta V_{ref} - Z_2 + \Delta V_F \qquad (3.58)$$

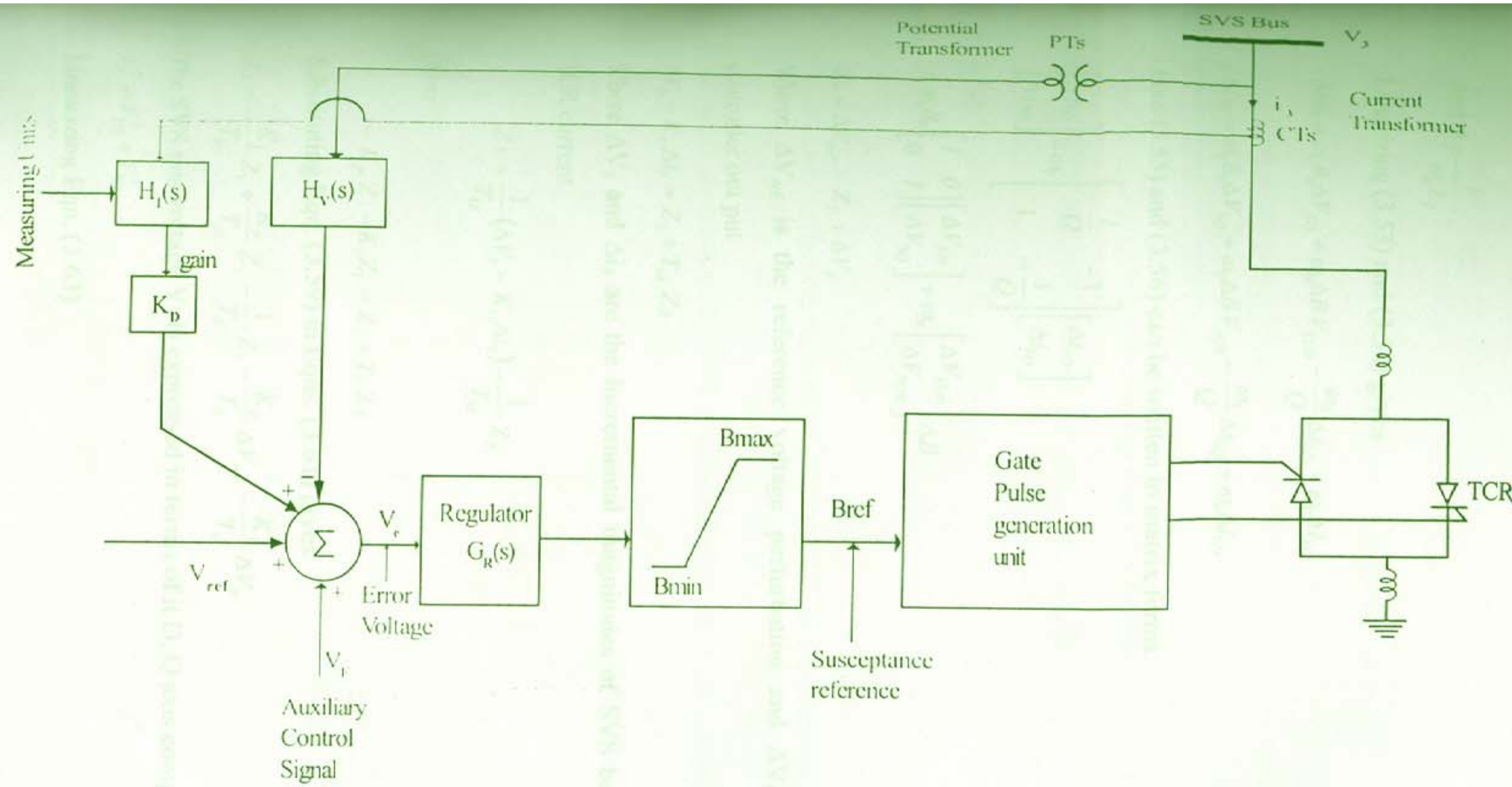


Fig.3.8 : Generator Control System Block Diagram for Thristorised SVS

Where ΔV_{ref} is the reference voltage perturbation and ΔV_F is auxiliary controller out put

$$\Delta V_3 - K_D \Delta i_3 = Z_2 + T_M \dot{Z}_2 \tag{3.59}$$

Where ΔV_3 and Δi_3 are the incremental magnitudes of SVS bus voltage are TCR current

$$\dot{Z}_2 = \frac{1}{T_M}(\Delta V_3 - K_D \Delta i_3) - \frac{1}{T_M} Z_2 \tag{3.60}$$

Also

$$-K_P \dot{Z}_1 - K_1 Z_1 = Z_3 + T_S \dot{Z}_3 \tag{3.61}$$

Substituting Eqn. (3.59) in Eqns. (3.61) gives

$$\dot{Z}_3 = -\frac{K_1}{T_S} Z_1 + \frac{K_P}{T_S} Z_2 - \frac{1}{T_S} Z_3 - \frac{K_P}{T_S} \Delta V_{ref} - \frac{K_P}{T_S} \Delta V_F \tag{3.62}$$

The SVS bus voltage V_3 is expressed in terms of it D, Q axis components as

$$V_3^2 = V_{3D}^2 + V_{3Q}^2 \tag{3.63}$$

Linearizing Eqn. (3.63)

$$\Delta V_3 = \frac{V_{3Do}}{V_{3o}} \Delta V_{3D} + \frac{V_{3Qo}}{V_{32o}} \Delta V_{3Q} \tag{3.64}$$

Similarly the magnitude of TCR currents is given by

$$i_3^2 = i_{3D}^2 + i_{3Q}^2 \tag{3.65}$$

Linearizing Eqns. (3.65) given

$$\Delta i_3 = \frac{i_{3Do}}{i_{3o}} \Delta i_{3D} + \frac{i_{3Do}}{i_{3o}} \Delta i_{3Q} \tag{3.66}$$

Substituting Eqn. (3.66) and (3.64) in Eqn. (3.52) gives

$$\dot{Z}_2 = \frac{1}{T_M}\left[(K_{VD}\,\Delta V_{3D} + K_{VQ}\,\Delta V_{3Q}) K_D (K_{iD}\,\Delta i_{3D} + K_{iQ}\,\Delta i_{3Q})\right] - \frac{1}{T_M} Z_2 \tag{3.67}$$

Where $K_{VD} = \dfrac{V_{3D0}}{V_{30}}$ and $K_{VQ} = \dfrac{V_{3Q0}}{V_{30}}$

And $K_{iD} = \frac{i_{3D0}}{i_{30}}$ *and* $K_{iQ} = \frac{i_{3Q0}}{i_{30}}$

The state and out put equation of the SVS model can for written as:-

Or $X_S = [A_S] X_S + [B_{S1}] U_{S1} + [B_{S2}] U_{S2} + [B_{S3}] U_{S3}$ (3.68)

The output equation of the SVS is constituted by the TCR current and is given by

$$+\begin{bmatrix} \frac{1}{L_S} & 0 \\ 0 & \frac{1}{L_S} \\ 0 & 0 \\ \frac{K_{VD}}{T_M} & \frac{K_{VQ}}{T_M} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta V_{3D} \\ \Delta V_{3Q} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ -\frac{K_P}{T_S} \\ 0 \end{bmatrix} \left[\Delta V_{ref}\right] + \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ -\frac{K_P}{T_S} \\ 0 \end{bmatrix} \left[\Delta V_F\right]$$

or $\dot{X} = [A_S] X_S + [B_{S1}] U_{S1} + [B_{S2}] U_{S2} + [B_{S3}] U_{S3}$ (3.69)

$[Y_S] = [C_S] X_S + [D_S] U_{S1}$ (3.70)

Where $Xs\left[\Delta i_{3D}\ \Delta i_{3Q}\ Z_1\ Z_2\ Z_3\ \Delta B\right]^t, U_{S1} = \left[\Delta V_{3D}\ \Delta V_{3Q}\right]^t$

$U_{S2} = \left[\Delta V_{ref}\right], [U_{S3}] = [\Delta V_F], Y_S = \left[\Delta i_{3D}\ \Delta i_{3Q}\right]^t$

or $[Y_S] = [C_S] X_S + [D_S] U_{S1}$ (3.71)

3.3 Development of the System Model

The state and output equations of the different constituent subsystems are combined resulting in the state equation of the overall system. The various subsystem models are so derived that inputs to any subsystem are directly obtained as output of the other subsystem fig. (3.9) considering the network transients. These interconnections correspond to a detailed representation of the generator and are valid for detailed as well simplified representation of the SVS.

The overall system model can be developed as follows

$\dot{X} = [A] X + [B] \Delta V_{ref}$ (3.72)

$$X = [X_R \; X_M \; X_E \; X_N \; X_S]^t, \quad B = [0 \;\; 0 \;\; 0 \;\; 0 \;\; B_{S2} \;\; 0]^t$$

The system matrix [A] is given by

A_R	$B_{R1}C_M$	$B_{R2}C_E$	$B_{R3}C_{N2}$	0
$B_{M1}C_{R1}$	$A_M + B_{M1}D_{R1}C_M$	0	$B_{M2}C_{N2}$	0
$B_ED_{N2}C_{R1} + B_ED_{N3}C_{R2}$	$B_ED_{N2}D_{R1}C_M + B_ED_{N3}D_{R2}C_M$	$A_E + B_E D_{N3} D_{R3}C_E$	$B_E C_{N1} + B_E D_{N1} D_S C_{N3} + B_E D_{N3} D_{R4} C_{N2}$	$B_E D_{N1} C_S$
$B_{N2}C_{R1} + B_{N3}C_{R2}$	$B_{N2}D_{R1}C_M + B_{N3}D_{R2}C_M$	$B_{N3}D_{R3}C_E$	$A_N + B_{N1}D_SC_{N3} + B_{N3}D_{R4}C_{N2}$	$B_{N1} C_S$
0	0	0	$B_{S1}C_{N3}$	A_S

CHAPTER 4

COMBINED REACTIVE POWER ANGLE CONTROLLER

4.1 Introduction

Auxiliary Control of SVS

It has been established that a SVS with only voltage control may not adequately contribute to the system damping (1,5). Significant enhancement in damping is achieved when SVS reactive power is modulated in response to auxiliary control signals superimposed over its voltage control loop. Various auxiliary control signals have been reported in the literature for system damping enhancement. These include, deviation in angular velocity (14,34), bus frequency, tie internal frequency. Discontinuous control strategies involving switching of TSR/TCR in accurately with active power flow in weak tie lines has also been suggested [16] for improving damping.

Auxiliary controller Design

The auxiliary controller has been assumed to be a single first order transfer function G (s) as shown in the fig. ,the effect of any general auxiliary controller is implemented through the auxiliary controller G (s) which is assume to be

$$G(s) = \frac{\Delta V_F}{\Delta Vref} = K_B\left[\frac{1+ST_1}{1+ST_2}\right] \qquad (4.1)$$

$$G(s) = K_B\frac{T_1}{T_2} + K_B\left[\frac{1-T_1/T_2}{1+ST_2}\right] \qquad (4.2)$$

from the block diagram

$$\frac{Z_C}{U_C} = K_B\left[\frac{1-T_1/T_2}{1+ST_2}\right] \qquad (4.3)$$

or $$\dot{Z}_C = -\frac{1}{T_2}Z_C + \left[\frac{K_B}{T_2}\left(1-\frac{T_1}{T_2}\right)\right]U_C \qquad (4.4)$$

or $$\dot{X}_C = [A_C]X_C + [B_C]U_C \qquad (4.5)$$

The output equation of the auxiliary controller is given by

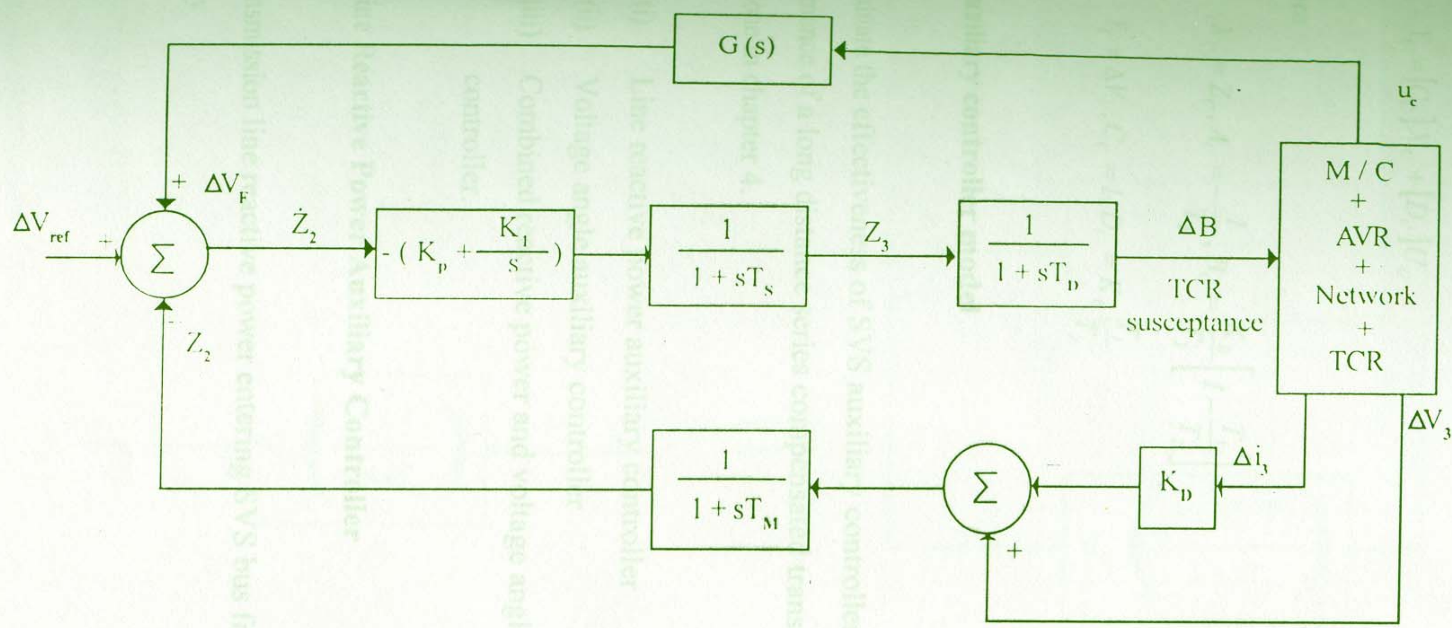


Fig.4.1 : SVS Control System with Auxiliary feedback

$$\Delta V_f = K_B \left[\frac{T_1}{T_2}\right] U_C + Z_C \qquad (4.6)$$

or $$Y_C = [C_C] X_C + [D_C] U_C \qquad (4.7)$$

Where

$$X_C = Z_C, A_C = -\frac{1}{T_2}, B_C = \frac{K_B}{T_2}\left[1 - \frac{T_1}{T_2}\right]$$

$$Y_C = \Delta V_F, C_C = 1, D_C = K_B \frac{T_1}{T_2}$$

4.2 Auxiliary controller model

To evaluate the effectiveness of SVS auxiliary controllers to enhance the dynamic performance of a long distance series compensated transmission line, design has been done in chapter 4.

(i) Line reactive power auxiliary controller
(ii) Voltage angle auxiliary controller
(iii) Combined reactive power and voltage angle (CPRVA) auxiliary controller.

4.2.1 Line Reactive Power Auxiliary Controller

The transmission line reactive power entering SVS bus from the generator end is given by

$$Q_2 = -(V_{3D} i_Q - V_{3Q} i_D) \qquad (4.8)$$

Linearizing Eqn. (4.8) gives the deviation in line reactive power ΔQ_2 which is selected as auxiliary control signal.

$$\Delta Q_2 = \left[V_{3D0}.\Delta i_Q + i_{Q0}\Delta V_{3D} - V_{3Q0}\Delta i_D - i_{D0}\Delta V_{3Q}\right] \qquad (4.9)$$

This is expressed in matrix form as

$$U_C = [F_{CR}]X_R + [F_{CM}]X_M + [F_{CE}]X_E + [F_{CH}]X_N + [F_{CS}]X_S \quad (4.3)$$

Where

$U_C = \Delta Q_2$ $F_{CR} = F_{CM} = F_{CE} = F_{CS} = 0$

$F_{CN} = [\ 0 - V3_{Q0}\ i_{Qo}\ V_{3D0} - i_{D0}]$

The suffix ‘o’ indicates the corresponding operating point values.

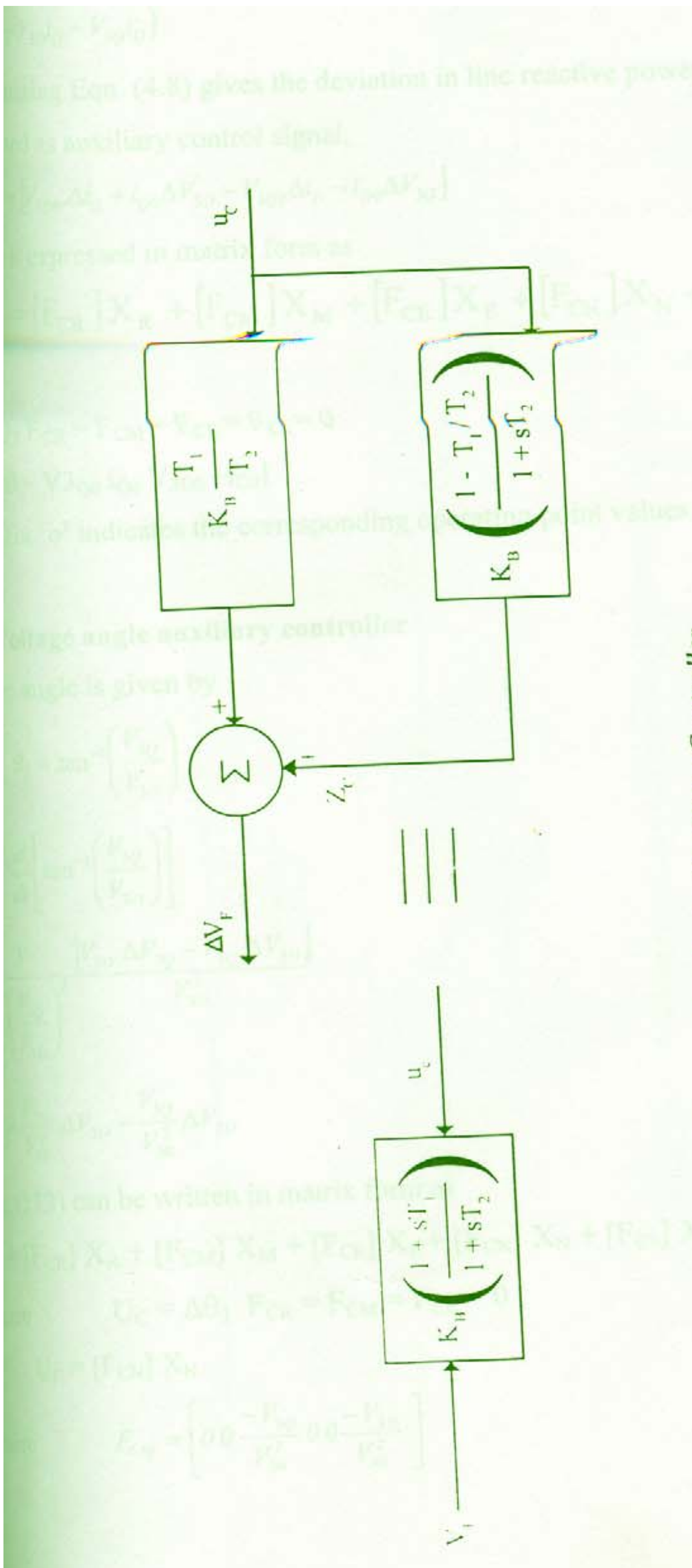


Fig. 4.2 : General First Order Auxillary Controller

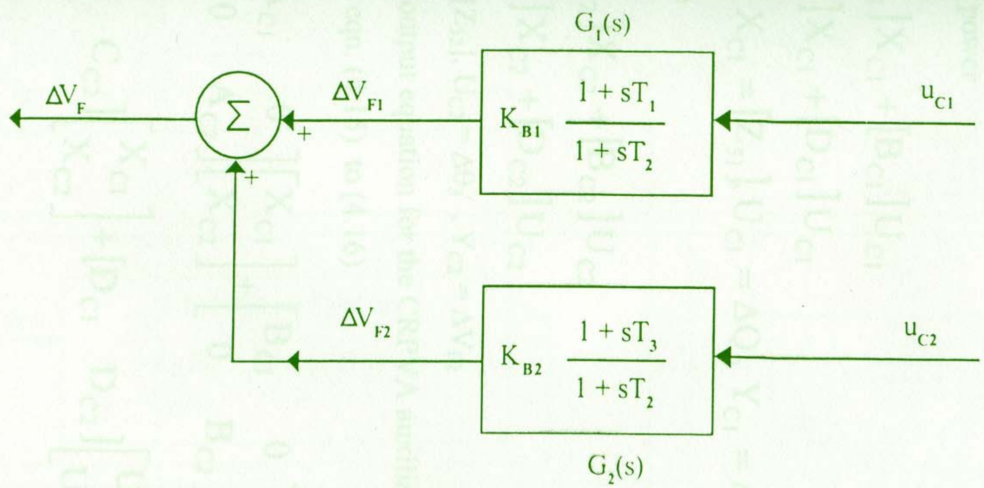


Fig.4.3 Control Scheme for C.R.P.V.A. Auxiliary Controller

4.2.2 Voltage angle auxiliary controller

Voltage angle is given by

$$\theta_3 = \tan^{-1}\left(\frac{V_{3Q}}{V_{3D}}\right) \quad (4.10)$$

$$\Delta\theta_3 = \frac{d}{dt}\left[\tan^{-1}\left(\frac{V_{3Q}}{V_{3D}}\right)\right]$$

$$= \frac{1}{1+\left(\frac{V_{3Q}}{V_{3D}}\right)^2}\frac{\left\lfloor V_{3D}\,\Delta V_{3Q} - V_{3Q}\,\Delta V_{3D}\right\rfloor}{V_{3D}^2} \quad (4.11)$$

$$\Delta\theta_3 = \frac{V_{3D}}{V_{30}^2}.\Delta V_{3Q} - \frac{V_{3Q}}{V_{30}^2}\Delta V_{3D} \quad (4.12)$$

Eqn. (512) can be written in matrix form as

$U_C = [F_{CR}]\ X_R + [F_{CM}]\ X_M + [F_{CE}]\ X_E + [F_{CN}]\ X_N + [F_{CS}]\ X_S$

Where $U_C = \Delta\theta_3 \quad F_{CR} = F_{CM} = F_{CE} = 0$ (4.13)

Or $U_C = [F_{CN}]\ X_N$ (4.14)

Where $F_{CM} = \left[0\,0\,\frac{-V_{3Q}}{V_{30}^2}\,0\,0\,\frac{-V_{3D}}{V_{30}^2}\right]$

$X_N = [\Delta i_{1D}\ \Delta i_D\ \Delta V_{3D}\ \Delta i_{1Q}\ \Delta i_Q\ \Delta V_{3Q}]$

4.2.3 Combined reactive power voltage angle (CRPVA) auxiliary controller.

The auxiliary signal in this case is the combination of line reactive power and the voltage angle signals with the objective of utilizing the beneficial contribution of both signals towards improving the dynamic performance of system. The control scheme for this composite controller is illustrated in fig (4.1). The auxiliary control signals U_{C1} and U_{C2} correspond respectively to the line reactive power and the voltage angle deviation, which are derived at the SVS bus. The state and output equation for the CRPVA auxiliary controller are obtained as follows

Line reactive power

$$\dot{X}_{C1} = [A_{C1}]X_{C1} + [B_{C1}]U_{C1} \tag{4.15}$$

$$Y_{C1} = [C_{C1}]X_{C1} + [D_{C1}]U_{C1} \tag{4.16}$$

Where $X_{C1} = [Z_{51}], U_{C1} = \Delta Q_2 \; Y_{C1} = \Delta V_{F1}$

Voltage angle

$$\dot{X}_{C2} = [A_{C2}]X_{C2} + [B_{C2}]U_{C2} \tag{4.17}$$

$$Y_{c2} = [C_{C2}]X_{C2} + [D_{C2}]U_{C2} \tag{4.18}$$

Where $X_{C2} = [Z_{52}]$, $U_{C2} = \Delta\theta_3$, $Y_{C2} = \Delta V_{F2}$

The state and output equation for the CRPVA auxiliary controller can be obtained by combining eqn. (4.15) to (4.16)

$$\begin{bmatrix} \dot{X}_{C1} \\ \dot{X}_{C2} \end{bmatrix} = \begin{bmatrix} A_{C1} & 0 \\ 0 & A_{C2} \end{bmatrix} \begin{bmatrix} X_{C1} \\ X_{C2} \end{bmatrix} + \begin{bmatrix} B_{C1} & 0 \\ 0 & B_{C2} \end{bmatrix} \begin{bmatrix} U_{C1} \\ U_{C2} \end{bmatrix}$$

$$[Y_C] = [C_{C1} \quad C_{C2}] \begin{bmatrix} X_{C1} \\ X_{C2} \end{bmatrix} + [D_{C1} \quad D_{C2}] \begin{bmatrix} U_{C1} \\ U_{C2} \end{bmatrix}$$

Where A_{C1}, B_{C1}, C_{C1} and D_{C1} are the matrices of the reactive power auxiliary controller and A_{C2}, B_{C2}, C_{C2} and D_{C2} are the matrices of the voltage angle auxiliary controller.

System Model With Auxiliary Controller

The system model incorporating auxiliary controllers now becomes

$$\begin{bmatrix} \dot{X}_R & \dot{X}_M & \dot{X}_E & \dot{X}_N & \dot{X}_S & \dot{X}_C \end{bmatrix}^t =$$

A_R	$B_{R1}C_M$	$B_{R2}C_E$	$B_{R3}C_{N2}$	0	0
$B_{M1}C_{R1}$	$A_M + B_{M1}D_{R1}C_M$	0	$B_{M2}C_{N2}$	0	0

$B_E D_{N2} C_{R1}$ + $B_E D_{N3} C_{R2}$	$B_E D_{N2} D_{R1} C_M$ + $B_E D_{N3} D_{R2} C_M$	A_E + $B_E D_{N3} D_{R3} C_E$	$B_E C_{N1}$ + $B_E D_{N1} D_S C_{N3}$ $+B_E D_{N3} D_{R4} C_{N2}$	0	0
$B_{N2} C_{R1}$ + $B_{N3} C_{R2}$	$B_{N2} D_{R1} C_M$ + $B_{N3} D_{R2} C_M$	$B_{N3} D_{R3} C_E$	A_N + $B_{N1} D_S C_{N3}$ $+B_{N3} D_{R4} C_{N2}$	$B_{N1} C_S$	0
$B_{S3} D_C F_{CR}$	$B_{S3} D_C F_{CM}$	0	$B_{S1} C_{N3}$ + $B_{S3} D_C F_{CN}$	A_S + $B_{S3} D_C F_{CS}$	$B_{S3} C_C$
$B_C F_{CR}$	$B_C F_{CM}$	0	$B_C F_{CN}$	$B_C F_{CS}$	A_C

$$\begin{bmatrix} X_R \\ X_M \\ X_E \\ X_N \\ X_S \\ X_C \end{bmatrix} + \left[0\;0\;0\;0\;B_{S2}\;\;0\right]^t \left[\Delta V_{ref}\right] \qquad (4.19)$$

CHAPTER 5

RESULTS AND CONCLUSION

TABLE1
SYSTEM EIGEN VALUES WITHOUT AUXILIARY CONTROLLER
(ORDER OF SYSTEM -31)

GENERATOR	EXCITATION SYSTEM	NETWORK	SVS
.1827±j4.9157	.8856-j0.9192	-3.2722±j3499.089	-10.3875±j198.8552
.8856+j0.9192	-25.7405±j24.1092	-3.2743±j2871.0850	-545.2881±j74.4143
-3.043		-13.2284±j2495.3310	-49.9113±j74.5450
-33.2525		-14.9278±j1867.3280	
-38.6339		-12.6906±j1137.8976	
		-12.9192±j443.9392	
		-18.9107±j510.1267	
		-5.0833±j311.4552	

The above table shows the eigen values for the system without auxiliary controller for dynamic performance enhancement using SVS. It is seen that the values which were in unstable mode become stable as shown in table 2.

TABLE2

SYSTEM EIGEN VALUES WITH CRPVA AUXILIARY CONTROLLER
(ORDER OF SYSTEM -33)

GENERATOR	EXCITATION SYSTEM	NETWORK	SVS
-0.5779+j0.8327	-25.6311±j23.7848	-3.2760±j3499	-9.6485±j205.567
-2.4507±j6.9546	-0.5779-j0.8327	-3.2733±j2781	-7.4132±j31.74
-2.9487		-13.244±j2495.53	-546.2729±j81.9032
-6.2984		-14.8923±j1867.43	-32.1727
-7.0022		-15.1640±1147.633	-142.0732
		-6.4257±j519.02	
		-12.8857±j446.7614	
		-4.9036±j309.1964	

The above table shows the system eigen values using the proposed Combined Reactive Power Angle Controller using SVS for the series compensated long transmission lines . It is seen that the eigen values in unstable mode have become stable now.

CONCLUSION

In this dissertation, a detailed system model consisting of a generating station supplying bulk power to a large power system , represented by an infinite bus has been used .The SVS is assumed to be of switched capacitor thyristor controlled reactor type configuration and is connected to transmission network through a coupling transformer. The network has been represented by a lumped parameter π circuit. The model reflects the dynamic of each component accurately over a wide operating range.

From table 1 and 2 , it is clear that the system eigen values become stable after using the proposed SVS Auxiliary controller.

Scope of further work

In the present scheme , an auxiliary controller is designed for dynamic performance enhancement of long Transmission Lines. The above controller can also be used for-

1. Transient study of the transmission lines.

2. Self tuning parameters of the SVS Auxiliary Controller that is K_B , T_1 ,T_2 can be found. Hence we can formulate self tuned Auxiliary Controller.

3. A new auxiliary controller for Active Power can also be developed.

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Appendix A-1

SYNCHRONOUS MACHINE MODEL PARAMETERS

The constants $a_1 - a_8$ are described as

$$\begin{bmatrix} a_1 & a_2 \\ a_3 & a_4 \end{bmatrix} = \frac{-\omega_o}{x_f x_h - x_{fh}^2} \begin{bmatrix} R_f x_h & -R_f x_{fh} \\ -R_h x_{fh} & R_h x_f \end{bmatrix}$$

$$\begin{bmatrix} a_5 & a_6 \\ a_7 & a_8 \end{bmatrix} = \frac{-\omega_o}{x_g x_k - x^2_{gk}} \begin{bmatrix} R_g x_k & -R_g x_{gk} \\ -R_k x_{gk} & R_k x_g \end{bmatrix}$$

The constants $b_1 - b_6$ are given as

$$b_1 = \frac{\omega_o R_f}{x_{df}}, \begin{bmatrix} b_2 \\ b_3 \end{bmatrix} = \frac{\omega_o}{x_f x_h - x^2_{fh}} \begin{bmatrix} R_f \left(x_{df} x_h - x_{dh} x_{fh}\right) \\ R_h \left(x_f x_{dh} - x_{fg} x_{df}\right) \end{bmatrix}$$

$$b_4 = \frac{\omega_o R_g}{x_{qg}}, \begin{bmatrix} b_5 \\ b_6 \end{bmatrix} = \frac{\omega_o}{x_g x_k - x^2_{gk}} \begin{bmatrix} R_f \left(x_{qg} x_k - x_{qk} x_{gk}\right) \\ R_k \left(x_g x_{qk} - x_{gk} x_{qg}\right) \end{bmatrix}$$

The constant c_1 - c_4 are given by

$$c_1 = \frac{x_{df} x_h - x_{dh} x_{fh}}{x''_d \left(x_f x_h - x^2_{fh}\right)} \quad , c_2 = \frac{x_{dh} x_f - x_{fh} x_{df}}{x''_d \left(x_f x_h - x^2_{fh}\right)}$$

$$c_3 = \frac{x_{qj} x_k - x_{qk} x_{gk}}{x''_d \left(x_g x_k - x^2_{qk}\right)} \quad , c_4 = \frac{x_{qk} x_g - x_{gk} x_{qg}}{x''_d \left(x_g x_k - x^2_{gk}\right)}$$

Where x_f, x_h, x_g, x_k are the reactances of the rotor coils specified by the subscripts.

R_f, R_h, R_g, R_k are the resistances of the rotor coils specified by the subscripts.

$x_{df}, x_{dh}, x_{fh}, x_{qk}, x_{qg}$ are mutual reactance's between rotor coils specified by the superscripts.

The resistances and reactances of various rotor coils are defined as follows:

$$x_{df} = x_{dh} = x_{fh} = x_d - x_l, x_{qg} = x_{qk} = x_{gk} = x_q - x_l$$

$$x_{hl} = \frac{\left(x''_d - x_1\right)\left(x'_d - x_1\right)}{\left(x'_d - x''_d\right)}, \quad x_{fl} = \frac{\left(x'_d - x_1\right)x_{df}}{\left(x''_d - x'_d\right)}$$

$$x_{gl} = \frac{\left(x''_q - x_1\right)\left(x'_q - x_1\right)}{\left(x'_q - x''_q\right)}, \quad x_{kl} = \frac{\left(x'_q - x_1\right)x_{qk}}{\left(x_q - x'_q\right)}$$

$$x_f = x_{df} + x_{fl}, x_h = x_{df} + x_{hl}, x_g = x_{qk} + x_{gl}, x_k = x_{qk} + x_{gl}, x_k = x_{qk} + x_{kl}$$

$$R_f = -\frac{x^2{}_{df}}{\omega_o T''_{do}\left(x_d - x'_d\right)}, \quad R_h = \frac{\left(x'_d - x_1\right)^2}{\omega_o T''_{do}\left(x'_d - x''_d\right)}$$

$$R_g = \frac{\left(x'_q - x_1\right)^2}{\omega_o T''_{qo}\left(x'_q - x''_q\right)}, \quad R_k = \frac{x^2{}_{qk}}{\omega_o T'_{qo}\left(x_q - x''_q\right)}$$

Where x_l is the stator leakage reactance.

x_d, x'_d, x''_d are the direct axes synchronous, transient and sub transient reactances respectively.

x_q, x'_q, x''_q are the quadrature axes synchronous, transient and sub transient reactance's respectively.

T'_{do}, T''_{do} are the direct axis transient and sub transient open circuit time constants respectively.

T'_{qo}, T''_{qo} are the quadrature axis transient and sub transient open circuit time constants respectively.

Appendix A -2

DERIVATION OF NETWORK OUTPUT EQUATIONS

The network output equations used in Sec.3.2.4 in chapter 3 are derived as given below:

The generator terminal voltage along α - β axis is given by

$$V_{g\alpha} = R_a i_\alpha + L''_d \left(\dot{i}_\alpha + I_\alpha \right)$$

$$V_{g\beta} = R_a i_\beta + L''_d \left(\dot{i}_\beta + I_\beta \right) \qquad \text{A (2.1)}$$

Eqns. A(2.1) are transformed to D-Q axis frame of reference and subsequently linearized as

$$\Delta V_{gD} = R_a \Delta i_d + L''(\Delta i_D + \Delta I_D) + \omega_o L'' d(\Delta i_Q + \Delta I_Q)$$

$$\Delta V_{gQ} = R_a \Delta i_Q + L'' d(\Delta i_Q + \Delta I_Q) - \omega_o L''_d (\Delta i_D + \Delta I_D) \qquad \text{A (2.2)}$$

At node – 2 in fig. 3.7, we have

$$i_\alpha = -(i_{3\alpha} + V_{3\alpha} j\omega_o C_n + i_{1\alpha}) \qquad \text{A (2.3)}$$

$$i_D + ji_Q = -(i_{3D} + ji_{3Q} + ji_{1Q} + i_{1D} + V_{3D} j\omega_o C_n - jV_{3Q}\omega_o C_n)$$

Comparing real and imaginary parts

$$i_D = -(i_{3D} + i_{1D} - \omega_o C_n V_{3Q})$$

$$i_Q = -(i_{3Q} + i_{1Q} + \omega_o C_n V_{3D}) \qquad \text{A (2.4)}$$

Linearizing Eqns. A (2.4)

$$\Delta i_D = -(\Delta i_{3D} + \Delta i_{1D} - \omega_o C_n V_{3Q})$$

$$\Delta i_Q = -(\Delta i_{3D} + \Delta i_{1Q} + \omega_o C_n V_{3D}) \qquad \text{A (2.5)}$$

Substituting the Δi_D, Δi_Q, and Δi_Q, Δi_D, in A(2.2), the output equation in terms of generator terminal voltage can be obtained as given in 3.38.

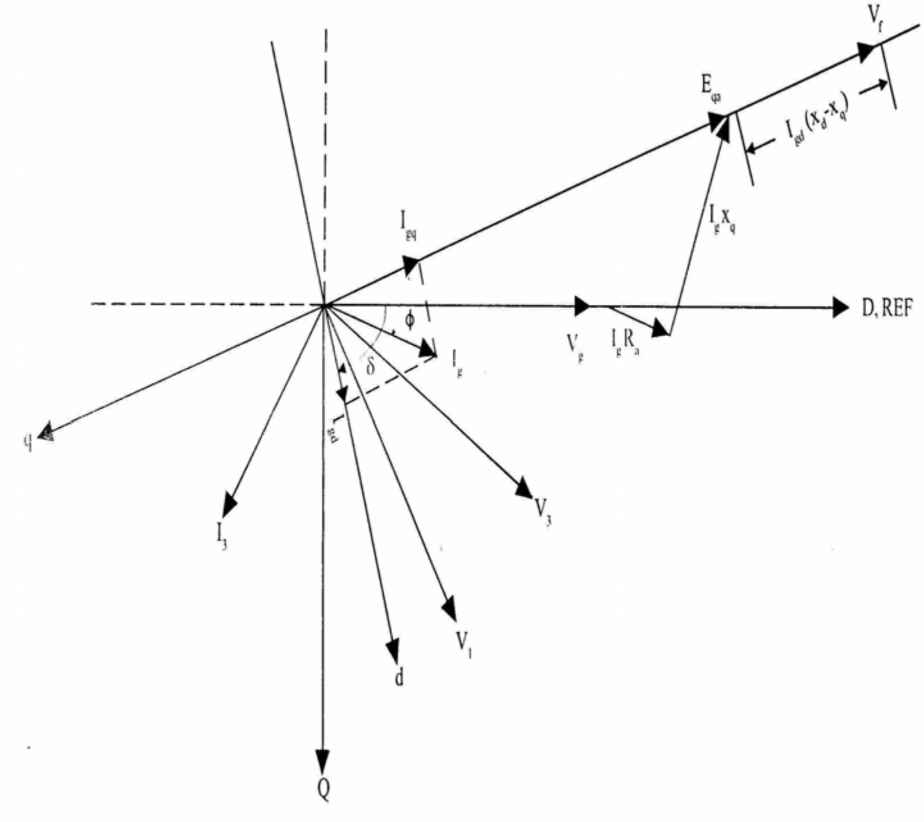

Fig.A 5.1 Vector Diagram of the System in Steady State