Damping of Subsynchronous Resonance using SSSC with hysteresis current control

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***Abstract* – Hybrid series compensation using static synchronous series compensator (SSSC) and passive series capacitor can improve the stability of the system, increases the power transfer capability. This paper analyzes the subsynchronous resonance (SSR) characteristics of the hybrid series compensated power system in detail and proposes a simple method to damp the oscillations. In this work, SSSC is modeled by a combination of three-level, 24 pulse configuration. Using the IEEE First Benchmark Model, the effectiveness of the proposed for mitigating SSR due to torsional interaction will be shown. The machine and circuit parameters are real values taken from the Navajo Project.**

***Index Terms*—Static synchronous series compensator (SSSC), Subsynchronous resonance (SSR), hybrid series compensation, torsional interaction, voltage source inverter.**

I. INTRODUCTION

A number of control devices under the term Flexible AC Transmission System (FACTS) have been proposed and implemented to improve the stability of transmission system. The FACTS devices can be used for power flow control, loop flow control, load sharing among parallel corridors, voltage regulation, and enhancement of transient stability and mitigation of system oscillations. Depending on the device used it is known as series compensation and shunt compensation. Hybrid series compensation is the combination of static synchronous series compensator (SSSC) and passive series capacitor. The potential inherent problem in series compensated transmission lines connected to turbo generators is subsynchronous resonance (SSR) leading to adverse torsional interactions [4]-[7] which results in shaft failure of mechanical system.

Series connected FACTS controllers has made it possible to regulate power flow and to counter the problem of SSR. Some of the series connected FACTS controllers are Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator. SSSC has several advantages over TCSC.

SSSC is a series compensator of FACTS family. It injects an almost sinusoidal voltage with variable amplitude. It is equivalent to an inductive or a capacitive reactance in series with the transmission line. The heart of SSSC is a VSI (Voltage Source Inverter) that is supplied by a DC storage capacitor. With no external DC link, the injected voltage has two parts: the main part is in quadrature with the line current and emulates an inductive or capacitive reactance in series with the transmission line, and a small part of the injected voltage is in phase with the line current to cover the losses of the inverter.[3]

SSSC is superior when compared to other FACTS devices and the benefits of using SSSC are:

- SSSC has one degree of freedom.
- Elimination of bulky passive components
- Possibility of connecting an energy source on the DC side to exchange real power with the AC network.

Several computer programs and analytical tools are available for the study of SSR caused by the interaction of multi mass turbine- generator and series compensated transmission systems. But there is a need in the electric power industry to compare study results, determine the reason for difference. To help meet this need, the IEEE Subsynchronous Resonance Task Force has prepared standard test cases. Using the Navajo Project 892.4 MVA generators and 500 KV transmission system as a guide, a standard network, two turbine generator models and data for two test cases have been provided.[1]

II. ANALYSIS OF SSR

A. Description of the system

Extensive SSR studies of the Navajo Project revealed that a simple radial RLC circuit, properly tuned, can produce both transient and self-excitation problems as severe as any observed in the analysis of the actual system. The single line diagram shown in Figure 1 represents such a simple circuit.[1]

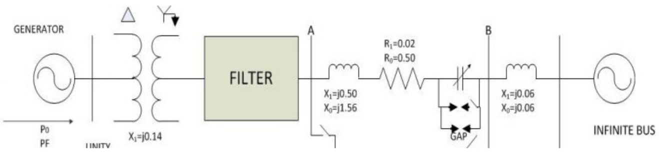

Figure 1: Network for Subsynchronous Resonance Studies

The circuit parameters expressed in per unit on the generator with rating at 60 Hz corresponds to the Navajo-McCullough line. Two fault locations are designated, and there is provision for inclusion of a filter. Two capacitor spark gaps are provided: a low voltage gap to bypass the capacitor during the fault and a high voltage gap to protect the capacitor during reinsertion [1]. This network is used for both transient and self excitation studies. Figure 2 represents the IEEE First Benchmark Model

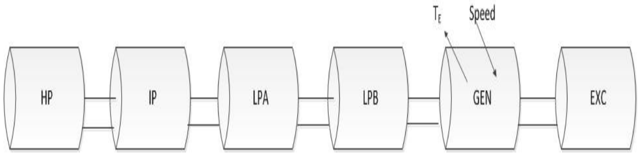

Figure 2: IEEE First Benchmark Model

B. Analysis

The SSR is analyzed based on damping torque, eigen value analysis and transient simulation. The steady state SSR is analyzed based on damping torque and eigen value analysis with linearized models at the operating point. The transient SSR is analyzed by transient simulation with nonlinear model of the system. The transmission line is modeled by lumped resistance and inductance to consider the effect of line transients.[2]

The mode frequencies are calculated with the help of inertia and spring constant [1] In case of IEEE FBM the parameters are

Mass	Inertia H (seconds)
HP	0.092897
IP	0.155589
LPA	0.858670
LPB	0.884215
GEN	0.868495
EXC	0.0342165

Shaft	Spring Constant (pu torque/rad)
HP-IP	19.303
IP-LPA	34.929
LPA-LPB	52.038
LPB-GEN	70.858
GEN-EXC	2.822

Depending on the above parameters the mode frequencies are

Mode 0-1.1026
Mode 1-15.9358
Mode 2-23.1469
Mode 3- 25.6135
Mode 4-32.2935
Mode 5-47.4563

Figure 3 indicates the mode shapes of IEEE FBM.

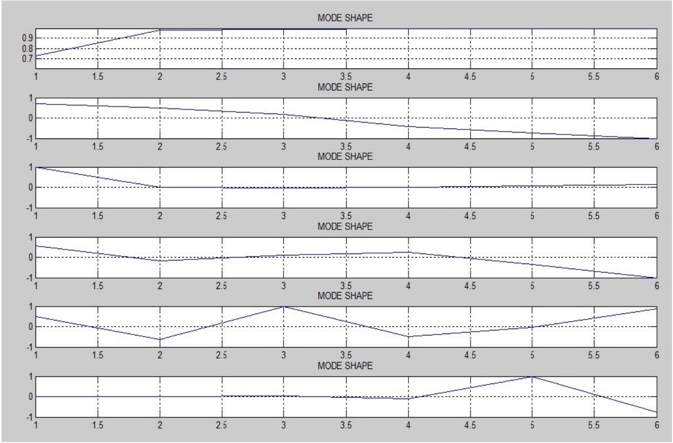

Figure 3-Mode Shapes

C. Subsynchronous Resonance

Sub synchronous resonance is an electrical power system condition where, electrical network exchanges energy with turbine generator at one or more natural frequency of the combined system, below the synchronous frequency of the system. For the IEEE first benchmark model the mode frequencies are calculated with the help of a MATLAB program. At these frequencies all rotating machinery system experience torsional oscillations to some degree during continuous or any disturbance operation in the power system. When the stress exceeds the endurance limit i.e. $45*10^7$ N/m^2, the shaft will be damaged. The stress is calculated as

$$Stress = \frac{\{(\delta_i - \delta_{i+1}) * G * R\}}{L}$$

where δ = twist angle
G =modulus of rigidity
R= Radius of shaft
L= Length of shaft

For the mode frequencies the stress exceeds the endurance limit of $45*10^7$ N/m^2. With the help of SSSC the stress at these frequencies can be reduced below the endurance limit.

III. STATIC SYNCHRONOUS SERIES COMPENSATOR

Static Synchronous Series Compensator (SSSC) is a series connected FACTS controller which is capable of providing reactive power compensation to a power system. The output of an SSSC is a series injected voltage, which leads or lags current by 90°, thus emulating a controllable inductive or capacitive reactance. SSSC can also be used to reduce the equivalent line impedance and enhance the active power transfer capability of the line [9].Figure 4 shows the schematic representation of SSSC

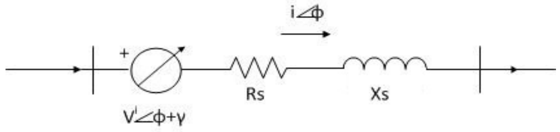

Figure 4: Schematic Representation of SSSC

A SSSC comprises of voltage source inverter and a coupling transformer that is used to insert the ac output voltage of the inverter in series with the transmission line. The magnitude and phase of this inserted ac compensating voltage can be rapidly adjusted by the SSSC controls. The SSSC injects the compensating voltage in series with the line irrespective of line current [3]. The transmitted power becomes a parametric function of the injected voltage and can be expressed as

$$P_q = \frac{V^2}{X_L} sin\delta + \frac{V}{X_L} V_q \cos\left(\frac{\delta}{2}\right)$$

The SSSC, therefore can increase the transmittable power, and also decrease it, simply by reversing the polarity of the injected ac voltage. The reversed (180° phase shifted) voltage adds directly to the reactive voltage drop of the line as if the reactive line impedance has increased. Apart from the stable operation of the system with both positive and negative power flows, SSSC has an excellent (sub cycle) response time and that the transition from positive to negative power flow through zero voltage injection is perfectly smooth and continuous.

IV. INTERNAL CONTROLS

From the standpoint of output voltage control, converters may be directly categorized as ‘directly’ and ‘indirectly’ controlled. For directly controlled converters both the angular position and the magnitude of the output voltage are controllable by appropriate gating whereas for indirectly controlled converters only the angular position of the output voltage is controllable by valve gating; the magnitude remains proportional to the dc terminal voltage. To provide reactive series compensation and handle SSR it can be done with the help of indirectly controlled converter. The method of maintaining a single frequency synchronous output independent of dc terminal voltage variation requires a directly controlled converter. Although high power directly controlled converters are more difficult and costly to implement than indirectly controlled converters.

V. CONTROLLING OF SSSC

As we know that SSSC consists of voltage source inverter and a coupling transformer. In this paper the controlling of SSSC is done by controlling the gate pulses of the inverter. The actual active and reactive powers are calculated by sensing the line voltage and current. These powers are compared with the actual powers to generate error signals. These error signals are fed to the controllers. The outputs of the controller are used to generate three phase reference voltage. Depending on the voltages, currents are calculated. These reference currents are compared with currents measured at the output of the inverter. The PWM current controller based on hysteresis is used to generate the gate pulses for the inverter switches [15]. The controller implemented is shown in Figure 5.

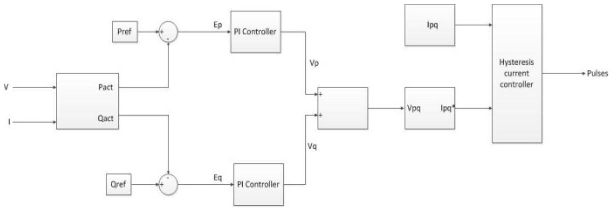

Figure 5: Controller of SSSC

VI. MODELLING OF SYSTEM

The control scheme of SSSC proposed in this paper is shown in Figure 5. It consists of two control loops. One is for reactive power control and another loop for active power control

Computation of power- The active power and reactive power are calculated with the help of V_{abc} and I_{abc} measured from the line.

$S=V_{abc}(I_{abc})^*=P_{act}+jQ_{act}$

These Pact and Qact are compared with the reference values and the errors are calculated as

Ep= Pref-Pact and Eq= Qref-Qact

These errors are fed to the controller and depending on the output injected voltage Vpq is calculated as:

$$V_{pq} = \frac{V_p + jV_q}{I^*_{abc}}$$

The magnitude of the injected voltage is given by

$$V_{pq} = |V_{pq}|$$

whereas the phase of the injected voltage is given by

$$\delta_{pq} = \tan^{-1}\left(\frac{Im(V_{pq})}{Re(V_{pq})}\right)$$

For the control of the power flow in the transmission line following inequalities are followed:

$0<V_{pq}<V_{pqmax}$ magnitude control

$0<\delta_{pq}<360°$ phase control

Three phase reference values of the injected voltage are given by:

$$V^*_{pqa} = \sqrt{2}V_{pq}\sin(\omega t + \delta_{pq})$$

$$V^*_{pqb} = \sqrt{2}V_{pq}\sin\left(\omega t + \frac{2\Pi}{3} + \delta_{pq}\right)$$

$$V^*_{pqc} = \sqrt{2}V_{pq}\sin\left(\omega t + \frac{4\Pi}{3} + \delta_{pq}\right)$$

The current controlled pulse width modulated voltage source inverter is used to inject ac voltage in series in the line. The three phase reference currents of the compensator are calculated as follows:

$$I^*_{pqa} = \frac{V^*_{pqa}}{Z_e}$$

$$I^*_{pqb} = \frac{V^*_{pqb}}{Z_e}$$

$$I^*_{pqc} = \frac{V^*_{pqc}}{Z_e}$$

Where $Z_e = R_e+jX_e$

The Voltage source inverter consists of IGBT switches with an anti parallel diode. This VSI is based on hysteresis current control. The schematic arrangement of hysteresis current control is shown in Figure 6

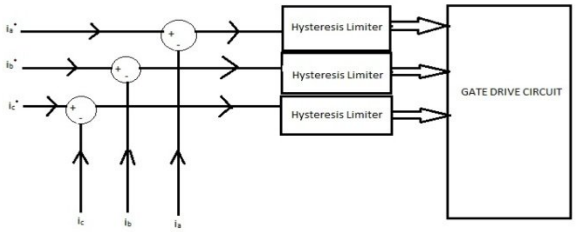

Figure 6: Schematic arrangement of hysteresis current control

VII. SIMULATION RESULTS

The proposed scheme is simulated in MATLAB R2010a and the whole scheme is shown in Figure 7.

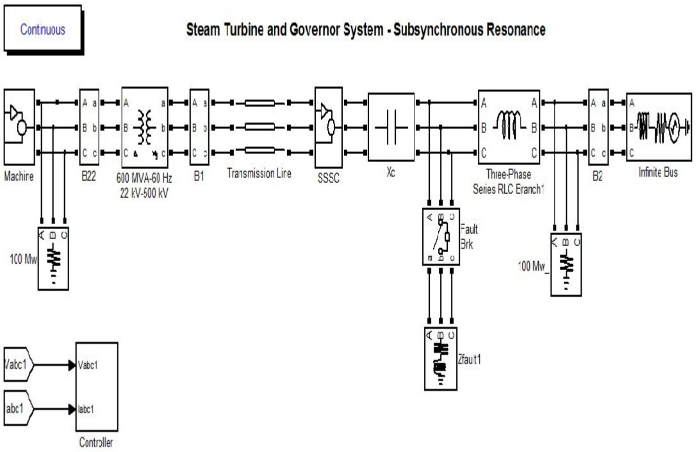

Figure 7: Simulated model of the whole system

With the induction of SSSC the stress is reduced to the endurance limit of $45*10^7$. At mode 1 i.e. frequency of 15.9358 Hz the stress gets reduced so that it does not damage the shaft.

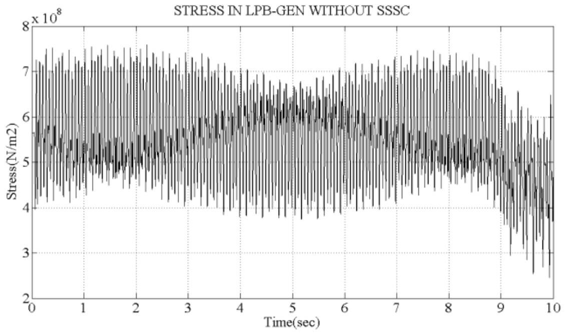

Figure 8: Dynamic response of GEN-LP stress without SSSC

Figure 8 and 9 shows the dynamic response of GEN-LPB stress without and with SSSC.

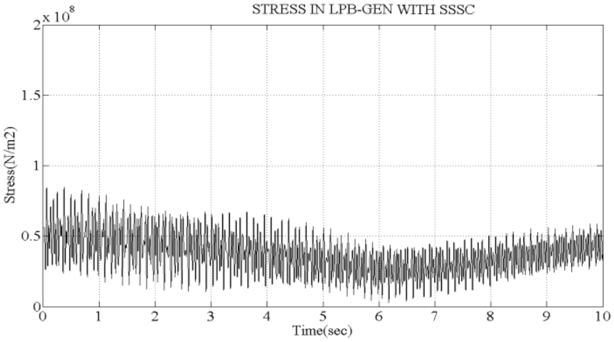

Figure 9: Dynamic response of GEN-LP stress with SSSC

Figure 10 and 11 shows the dynamic response of GEN-LPB torque without and with SSSC

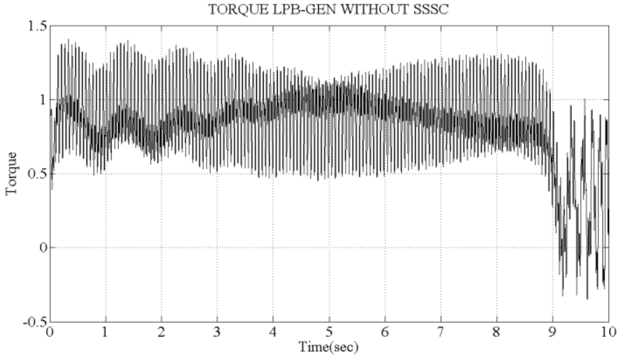

Figure 10: Dynamic response of GEN-LPB torque without SSSC

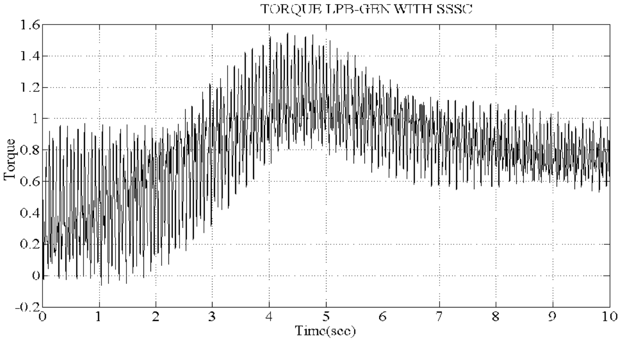

Figure 11: Dynamic response of GEN-LPB torque with SSSC

Figure 12 and 13 shows the dynamic response of load angle delta without and with SSSC

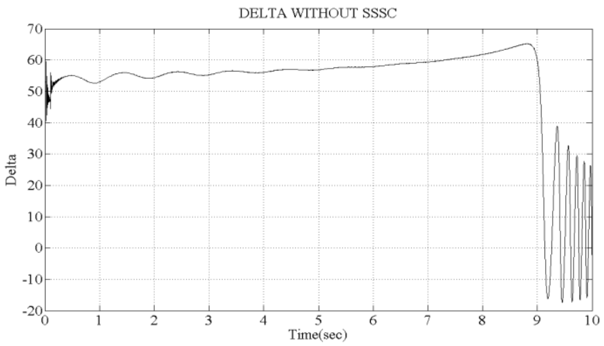

Figure 12: Dynamic response of delta without SSSC

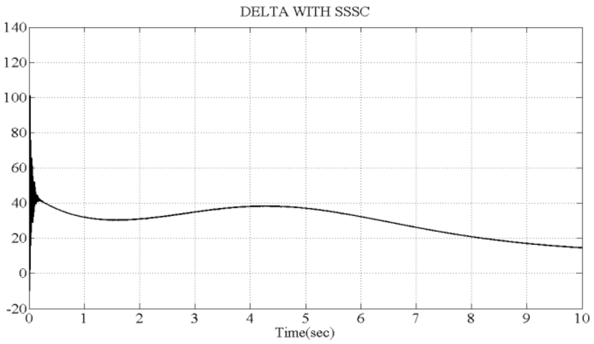

Figure 13: Dynamic response of delta with SSSC

VIII. CONCLUSIONS

It has been found that the SSSC injects the fast changing voltage in series with the line irrespective of the magnitude and phase of the line current and the same SSSC damp out the oscillations of the system and keeps the stress within the endurance limit.

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