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Mitigation of SSR in Series Compensated Power System Using a FACTS based Subsynchronous Damping Controller

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Abstract:

Due to the continuous increase in the demand of electricity, we are left with two options; either to increase the installed generating capacity in proportion with the rise in demand or to use some other methods along with former; keeping the stability intact. In this regard series capacitive compensation comes at our rescue. Series capacitive compensation virtually reduces the length of transmission line by minimizing the line inductive reactance and enhances the power transmission capacity. However, in 1971 it was learned in one of the USA's Mohave thermal power plant that series capacitors can create an adverse interaction between the series compensated electrical system and the spring-mass mechanical system of the turbine-generators. This effect is called sub synchronous resonance (SSR). Due to this torsional oscillation, the rotor shaft faces severe fatigue and can be damaged if a proper solution is not adopted to mitigate SSR. There are many methods proposed in literature for SSR mitigation.However this paper proposes that SSR can be mitigated with a proper gating pulse to TCSC. A Subsynchronous damping controller(SSDC) is proposed to be modeled for detecting SSR phenomena. SSDC observes this SSR phenomenon and directs an appropriate signal to the TCSC automatically. Thyristor controlled series capacitor (TCSC) which improves transmission line capability, can also be used in damping out Sub synchronous resonance (SSR) efficiently.All results are validated using simulations in MATLAB.

***Keywords*: Sub synchronous damping controller (SSDC), Torsional Interaction, sub synchronous resonance(SSR), TCSC**.

I. INTRODUCTION

Due to re-structuring of the power market, use of new technologies and controls, aging of the power system infrastructures, operating in highly stressed conditions, stability of the power system becomes increasingly important. Currently, voltage stability, frequency stability, transient stability, inter -area oscillations are of great concern. As the interconnected power system becomes more complicated, more accurate system modeling is required to analyze various stability issues [11]. Capacitors are connected in series with the line conductors to compensate for the inductive reactance of the line. It reduces the transfer reactance between the buses with which the line is connected. Series compensation increases the maximum power that can be transmitted, & lowers the effective reactive power (I^2X) loss. There are many methods proposed in literature for SSR mitigation [2][3][4][5][10][11] etc.

This paper proposes that SSR can be mitigated with a proper gating pulse to TCSC. In order to detect this SSR; sub synchronous damping controller (SSDC) is designed in MATLAB SIMULINK software. SSDC observes these SSR phenomena and directs an appropriate signal to the TCSC automatically.

Series capacitors can create an opposite interaction between the series compensated electrical system and the multi spring-mass mechanical system of the turbine-generators. This effect is called sub synchronous resonance (SSR). An IEEE committee report (1985) has defined SSR as "sub synchronous 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".

II. TYPES OF SSR INTERACTION

There are three aspects of SSR which are best known as Induction Generator Effect, Torsional Interaction Effect and Transient Torque Effect.

A. *Induction Generator Effect*

This is purely an electrical phenomena. Three phase current at a frequency known as sub synchronous frequency can result due to fault or a nearby network disturbance. When the sub synchronous frequency currents flow through the generator armature, they view the synchronously rotating rotor‟s circuit as negative resistance. If this fictitious negative resistance is more than the sum of the armature and network resistance, the electrical system is self excited. Such self-excitation would be expected to cause excessive voltage and current.

B. Torsional Interaction

Torsional interaction SSR is observed when the induced sub synchronous torque in the generator is close to one of the torsional natural modes of the turbine generator shaft. When this happens, generator rotor oscillations will build up and this motion will induce armature voltage components at both sub synchronous and super synchronous frequencies. Moreover, the induced sub synchronous frequency voltage is able to sustain the sub synchronous torque. If this torque equals or exceeds the inherent mechanical positive damping of the rotating system, the system will become self-excited. This phenomenon is called “torsional interaction."

C. Transient Torque

Transient torques results from system disturbances. System disturbances cause sudden changes in the network, resulting in sudden changes in currents that will tend to oscillate at the natural frequencies of the network. These transients are always dc transients, which decay to zero with a time constant that depends on the ratio of inductance to resistance; for a transmission system without series capacitive compensation. Transient currents will contain one or more oscillatory frequencies for a series capacitive compensated line which further depends on the network capacitance as well as the inductance and resistance. A simple radial R-L C system will have only one such natural frequency, but in a network with many series capacitors there will be many such Sub synchronous frequencies.

III. CASE STUDY

IEEE FBM is modified to include TCSC for the study of SSR. The single line diagram of a Single Machine Infinite Bus system given by IEEE subsynchronous resonance task force committee for SSR study is shown in fig.1.

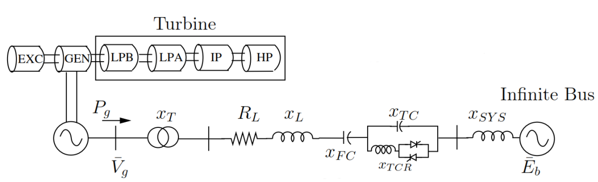

Fig. 1. The IEEE first benchmark model with a TCSC.

The single-line diagram shown represents a three-phase, 60 Hz, 735 kV power system transmitting power from a power plant consisting of six 350 MVA generators to an equivalent system through a 600 km transmission line. The transmission line is broken into two lines of 300 km each, connected between buses B1, B2, and B3. A 100 MW series R-L-C load is connected between generator and transformer. For transmission capacity enhancement, each line is series compensated by capacitors representing 55% of the line reactance. Ref fig (1).

IV. SPRING-MASS MODEL OF THE TURBINE GENERATOR SHAFT

Figure 2 shows a simplified mass representation of parts of a steam turbine generator. For the simplicity in understanding of Matrices, a four mass rotor system is considered. Mass 2 and 3 could either be Generator and LP or combinations of any two masses conjoining each other except the extreme left and extreme right for better illustration.

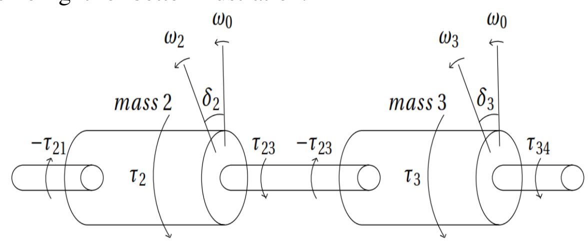

Fig 2. Spring-mass representation of parts of a steam turbine rotor in terms of Inertia, Torque & Angular frequency

When Newton’s second law is applied to the mass number 2, the motion equation is given by

$$J_2 \frac{d\delta_2^2}{dt^2} = \tau_2 - \tau_{21} + \tau_{23} \quad \text{.......... ....(1)}$$

Where

τ_2 → Applied torque on mass 2
τ_3 → Applied torque on mass 3
ω_0 → Angular frequency of the system
ω_2 → Angular frequency of the mass 2
ω_3 → Angular frequency of the mass 3
δ_2 → Resulting displacement of the mass 2
δ_3 → Resulting displacement of the mass 3
J_2 → Moment of inertia for mass 2
τ_{21} → Torque between masses 1 and 2
τ_{23} → Torque between masses 2 and 3
D_{22} → Self damping of mass 2

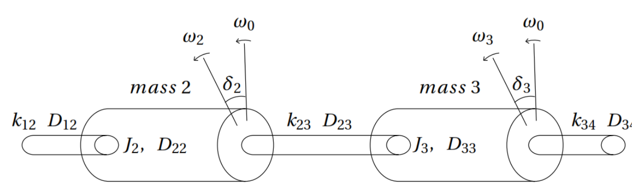

Fig 3: Mass representation of parts of a steam turbine rotor in terms of inertia, stiffness and damping constants.

The shaft torques for masses 1 and 2 is combindly given by the equation:

$$\tau_{21} = k_{21}(\delta_2 - \delta_1) + D_{21}\left(\frac{d\delta_2}{dt} - \frac{d\delta_1}{dt}\right) \quad \text{..................(2)}$$

The shaft torques for masses 2 and 3 is combindly given by the equation:

$$\tau_{23} = k_{23}(\delta_3 - \delta_2) + D_{23}\left(\frac{d\delta_3}{dt} - \frac{d\delta_2}{dt}\right) \quad \ldots\ldots\ldots\ldots\ldots(3)$$

From equation (1),(2) and (3)

$$J_2\frac{d\delta_2^2}{dt^2} = \tau_2 - k_{21}(\delta_2 - \delta_1) - k_{23}(\delta_2 - \delta_3) - D_{21}\left(\frac{d\delta_2}{dt} - \frac{d\delta_1}{dt}\right) - D_{23}\left(\frac{d\delta_2}{dt} - \frac{d\delta_3}{dt}\right) - D_{22}\frac{d\delta_2}{dt} \quad (4)$$

If now difference between the system angular frequency and the angular frequency of the mass 2 is given as $\Delta\omega_2 = \omega_2 - \omega_0$.

It concludes that there will be two state variables for each mass in the system.

Since $\Delta\omega_2 = \frac{d\delta_2}{dt}$, equation (4) can be written as below:

$$J_2\frac{d\Delta\omega_2}{dt} = \tau_2 - k_{21}(\delta_2 - \delta_1) - k_{23}(\delta_2 - \delta_3) - D_{21}(\Delta\omega_2 - \Delta\omega_1) - D_{23}(\Delta\omega_2 - \Delta\omega_3) - D_{22}\Delta\omega_2 \quad (5)$$

It is the first order equation. For each mass in the system, there will be an equation similar to above.

By considering the angle and angular frequency state variables, the equations can be represented by a matrix equation on the form

$$\dot{x} = Ax + Bu \quad \ldots\ldots\ldots\ldots\ldots(6)$$

where A is the state matrix, B is the driving matrix, x is a vector of state variables such as the angles δ of equation (4) and u a vector of inputs, here the change in torque Δ τ applied to each mass.

Meanwhile to find the natural frequency of the rotor, the change in input torque (u=0) is assumed zero, thus equation (6) becomes as follows:

$$\dot{x} = Ax \quad \ldots\ldots\ldots\ldots\ldots(7)$$

This equation can be used to find the natural frequencies of the rotor. The state matrix A for a four mass system is given by

$$A = \begin{bmatrix} 0 & 1 \\ K & D \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots(8)$$

Where 0 is a null matrix, 1 is Identity matrix, K is the stiffness matrix and D is the damping matrix. For a four mass system, the K and D matrices can be written as:

$$K = \begin{bmatrix} \frac{-k_{12}}{J_1} & \frac{k_{12}}{J_1} & & \\ \frac{k_{12}}{J_2} & \frac{-k_{12}-k_{23}}{J_2} & \frac{-k_{23}}{J_2} & \\ & \frac{k_{23}}{J_3} & \frac{-k_{23}-k_{34}}{J_3} & \frac{k_{34}}{J_3} \\ & & \frac{k_{34}}{J_4} & \frac{-k_{34}}{J_4} \end{bmatrix} \quad \ldots\ldots(9)$$

$$D = \begin{bmatrix} \frac{-D_{12}-D_{11}}{J_1} & \frac{D_{12}}{J_1} & & \\ \frac{D_{12}}{J_2} & \frac{-D_{12}-D_{23}-D_{22}}{J_2} & \frac{D_{23}}{J_2} & \\ & \frac{D_{23}}{J_3} & \frac{-D_{23}-D_{34}-D_{22}}{J_3} & \frac{D_{34}}{J_3} \\ & & \frac{D_{34}}{J_4} & \frac{-D_{34}-D_{44}}{J_4} \end{bmatrix} \quad \ldots\ldots(10)$$

The matrix B can be written as:

$$B = \begin{bmatrix} 0 & J^{-1} \end{bmatrix}^T \quad \ldots\ldots\ldots\ldots\ldots(11)$$

Where J^{-1} is a 4 X 4 matrix for four mass system and a 6 X 6 matrix for a six mass system.

V. MULTI SPRING-MASS MODEL OF THE TURBINE-GENERATOR SHAFT

The turbine-generator mechanical system consists of six masses; namely high-pressure turbine (HP), intermediate-pressure turbine (IP), low pressure turbine A (LPA) and low pressure turbine B (LPB), an exciter (EXC), and a generator (GEN) coupled to a common shaft as shown in Fig.4. Every mass is considered as lumped masse (i.e. rigid body) connected to each other via massless springs.

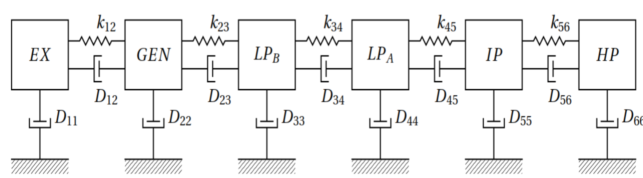

Fig 4. Mechanical representation of IEEE FBM model for SSR

The modes oscillation of IEEE FBM multi-mass model can be calculated using MATLAB SIMULINK software. Linearization is done of non-linear time variant system with the help of MATLAB. When we add linear analysis points, the software adds markers at their respective locations in the model. For this example, use the model operating point for linearization. In the Operating Point drop-down list, leave Model Initial Condition selected. It is done to find the number of modes will be decided by number of masses. Linearization is useful in model analysis and control design applications. After we linearize a Simulink model at a specific operating point, we can use your linear model to obtain linear state-space, transfer-function, Analyze and compare plant response near different operating points and design linear controller [15].

The modes of oscillations of an standard six mass IEEE FBM mechanical model's rotor is given below [11]:

Table 1: Modes of oscillations of IEEE FBM six mass model

Mode no.	1	2	3	4	5	6
Frequency [Hz]	14.4	14.4	18.5	23.3	29.5	43.1

VI. SIMULATION AND RESULTS

The MATLAB simulation model for the study and mitigation of SSR is shown in figure below:

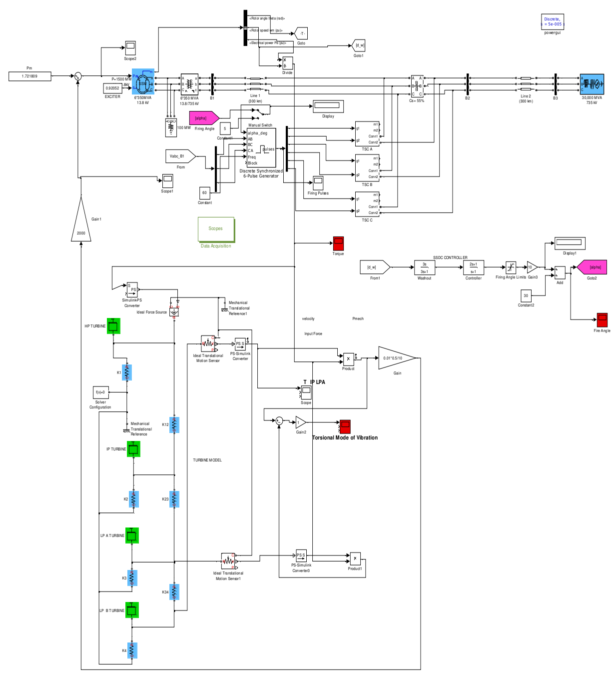

Fig.5. MATLAB SIMULINK model of three phase series compensated transmission network for TCSC based SSDC

A. *Impact of SSR on The System Without SSDC:-*

The Manuel switch is open. It means the subsynchronous damping controller is not connected in the system. It means the value of firing angle (α=constant) is constant and is kept 10 degree.

1. Transient Torque:- MATLAB simulation is done and transient torque is observed as shown in figure. We can observe a continuously propagating envelope. Ref Fig (6)

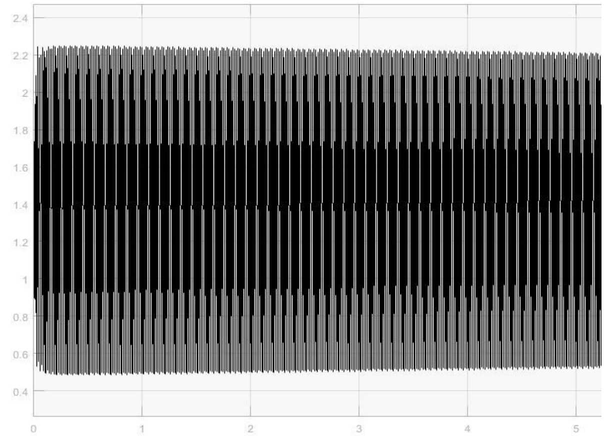

Fig 6. Transient Torque envelope without SSDC.

2. Torsional Oscillation:- Torsional oscillations are also plotted for the same condition and an expanded oscillating envelope can be seen which is prone to put the stability in danger. Ref fig (7).

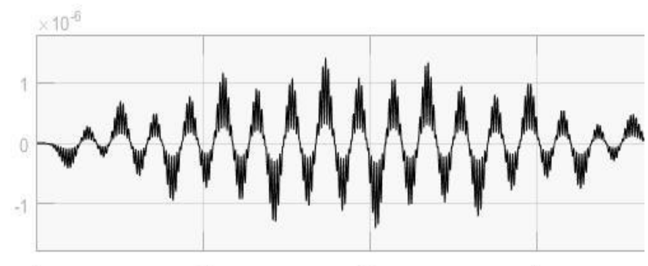

Fig 7. Torsional oscillations envelope without SSDC.

B. *Impact of SSR on The System With SSDC:-*

To examine the impact of subsynchronous damping controller on the SSR, the manual switch is put on. Now since the SSDC is inserted in the system, it will keep changing the value of Thyristor's firing angle (α= variable) automatically for the mitigation of Transient Torque and Torsional oscillations. Ref Fig.(8)

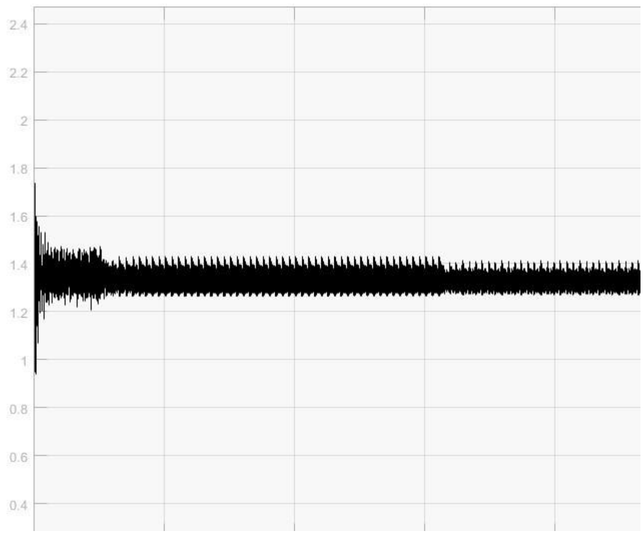

Fig 8. Transient Torque envelope with SSDC.

At the beginning the transient torque envelope size is more which is reduced very rapidly up to a satisfactory value.

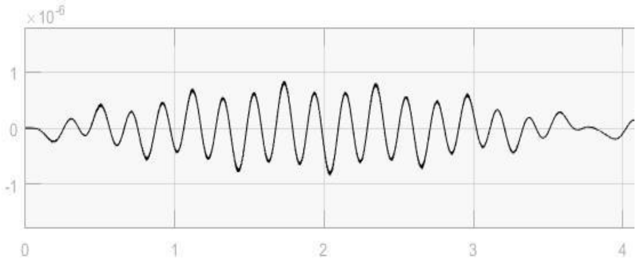

Fig 9. Torsional oscillations envelope with SSDC.

We can observe the reduction of Torsional oscillations upto the extent of being completely nullified.

C. Insertion of SSDC in the mid of Simulation:-

In order to get more more clarity in the study of impact of SSDC upon a series capacitive compensated power system; the controller is introduced in the mid of simulation in the IEEE FBM modified model. We can clearly observe the mitigation of Transient Torque up to a larger extent. It can also be witnessed that an SSDC can play a significant role in suppressing the torsional oscillations and transient torque. As shown in the Fig 9, the transient torque envelope is thinned. Also torsional vibrations are almost eliminated completely.

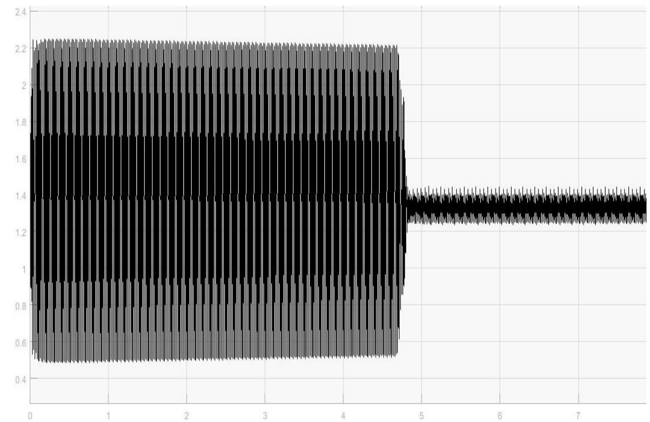

Fig 10. Transient Torque envelope when SSDC is connected at the mid of simulation.

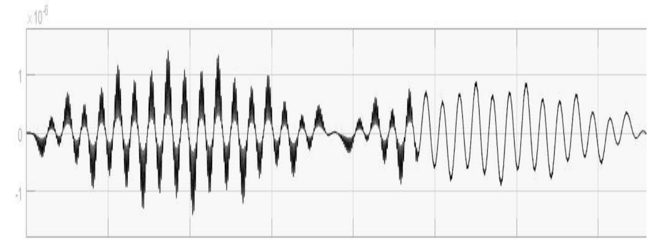

Fig 11. Torsional Oscillation envelope when SSDC is connected at the mid of simulation.

CONCLUSION

As we can see that SSDC is capable of mitigating the most of the vital aspects of SSR phenomena. The torsional oscillations are almost nullified when the damping controller is suddenly inserted in the system. Transient Torque also seems to be reduced up to a very satisfactory level. Further analysis can be done by altering the values of fixed capacitances and thyristor firing angles. It can further be analyzed that at which "α" value the SSR is most pronounced.

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