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Study of Subsynchronous Resonance in Power Systems

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***Abstract*— Turbine-generators have torsional natural frequencies due to physical properties of their long multi-element shafts. Series capacitor compensation in ac transmission networks has a tendency to reduce damping of torsional vibrations of nearby turbine generators. The phenomenon is called subsynchronous resonance (SSR), and it affects turbine-generators at subsynchronous frequencies that are specific to torsional oscillation modes of individual units. Series capacitors also have a tendency to amplify the shaft stress during major network transient events. The mechanism of the subsynchronous resonance is well understood. This paper first provides an overview of subsynchronous resonance (SSR) and the impact of series compensation on SSR, then other cases are mentioned other than series capacitor where it can also cause severe damages to machines and equipment. The paper also provides descriptions of technical methods for mitigating SSR problems. The subsynchronous resonance (SSR) for IEEE second benchmark system is simulated using Matlab based on the Power System Block-set in conjunction with Simulink. The effects of both series compensation level and fault clearing time on SSR are investigated. The results obtained verify the influence of both fault clearing time and series compensation level on maximum magnitudes of the turbine-generator shaft torques have been analysed using time domain simulation technique.**

***Index Terms*—SubSynchronous Resonance, Matlab, Torque Amplification, Second Benchmark Model**

I. Introduction

Series capacitor compensation in AC transmission systems is a way to increase load carrying capability, control load sharing among parallel lines and enhance transient stability. Series Capacitive compensation in transmission lines may cause subsynchronous resonance that can lead to turbine-generator shaft failure and electrical instability at oscillation frequencies lower than the normal system frequency. Therefore, proper understanding and analysis of SSR is to be carried out while planning series capacitor compensation in power systems. The main concern with SSR from torsional stresses is the possibiility of shaft damage. Damage can result from the long term cumulative effects of low amplitude torsional oscillations or the short term effects of high amplitude torques. The mechanical parameters are less prone to SSR in hydro power stations than thermal power stations. [1]

Subsynchronous resonance is addressed in three categories, i.e., induction generator effect, torsional interaction and torque amplification. In all cases, subsynchronous resonance is due to the interaction of a series capacitor with turbine-generator. The first two types are caused by a steady state disturbance, while the third is excited by transient disturbances. [2]

In past few years it was found that other circumstances can also lead to an electromechanical resonance without capacitors being used to compensate transmission lines. Damages can also occur in these phenomenons. The following cases will be presented in this paper an example for the SSR phenomenon, SSR caused by feedwater pumps fed by thyristor cascades, electro-mechanical resonance during running up of a squirrel cage induction machine and SSR caused by slip ring machines with faulty rotor windings connected to a close meshed private power system with synchronous generators. [3]

In this paper, an important application of the second benchmark system and Matlab is presented to study subsynchronous resonance that may occur in series compensated transmission systems – in particular, the simulation of the torque amplification and eigenvalue analysis of the electrical network. The subsynchronous resonance damping under different levels of series compensation in the network, and the effect of fault clearing time on the torque amplification are investigated.

II. SubSynchronous Resonance

Subsynchronous oscillation is an electric power system condition where the electric network exchanges significant energy with a turbine-generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system following a disturbance from equilibrium. The above excludes the rigid body modes of the turbine-generator rotors.

A typical rotor of a large turbine-generator consists of several rotating sections of the turbine, a generator rotor, and often a rotor of a rotating exciter that are connected with coupling shafts. Mathematically, the rotor is a spring-mass system where coupling shafts act as torsional springs and the moment of inertia of each rotating section acts as mass. It has intrinsic modes of torsional vibration. The electrical torque of the generator can act as a forcing function to excite the torsional vibration modes. Conversely, the torsional vibration modulates the generator output voltage and excites the electrical oscillation at the fundamental (50Hz or 60Hz) complement frequency of the torsional vibration. For example, a 25Hz torsional oscillation on a generator connected to a 60Hz system will generate 35Hz electrical oscillations. This condition typically requires the turbine-generator to be connected radial or nearly radial to a series compensated transmission line. [4]

Mechanical damping for torsional vibrations is always positive but small which is mainly due to friction, wind losses, and steam flow (or gas flow) around the rotor. Mechanical damping is lowest when a turbine-generator is at no-load, and increases with the load. Measured no-load damping for steam turbine-generator torsional modes is typically in the range of 0.02 sec-1 to 0.05 sec-1. It is very small due to the small amount of steam flowing in the turbine at no-load. The fullload damping is around 0.2 sec-1 or more. No-load damping is significantly higher for a gas turbine-generator because the coaxial compressor operating at the rated speed is a significant shaft load (typically 20 to 25% of rated generator output). There is significant gas flow (or airflow) in both the turbine and compressor stages even at no-load. Measurement on a particular gas turbine-generator yielded no-load damping of 0.1 sec-1, and estimated full load damping is 0.3 sec-1. [4]

Subsynchronous resonance (SSR), as defined here, encompasses the oscillatory attributes of electrical and mechanical variables associated with turbine generators when coupled to a series capacitor compensated transmission system where the oscillatory energy interchange is lightly damped, undamped, or even negatively damped and growing. The electrical system frequency for a simple radial system (as shown in Figure 1) is calculated using Equation (1)

$$f_{er} = f_o \sqrt{\frac{X_c}{X'' + X_E + X_T}} \dots \dots (1)$$

with reactances X defined at frequency f_0, the electrical frequency corresponding to the rotor average speed. The frequency f_0 is equal to the synchronous frequency under ideal conditions.

A resonant circuit yielding a single natural frequency is shown in Figure-1. But the series compensated transmission system is more complex resulting in more than one natural frequency. Frequencies below and above the frequency corresponding the rotor speed are called subsynchronous & supersynchronous frequencies. Thus, f_{er} denotes the subsynhronous natural frequencies of the natural system.

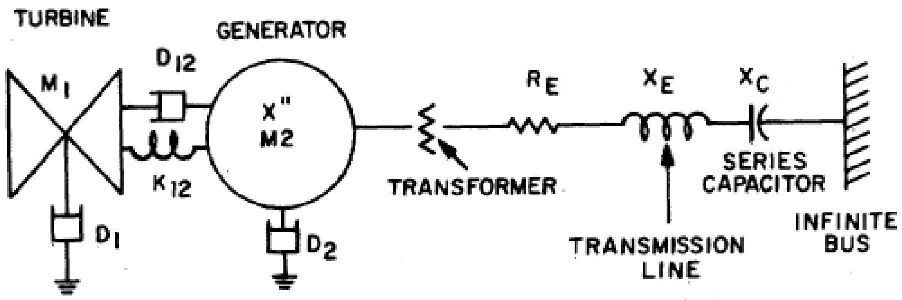


Figure-1 Turbine-Generator with Compensated Transmission

A. Incution Generator Effect

Currents of resonant frequency (f in the electrical system give rise to rotor current of frequency fr as indicated in Equation-2. A three-phase set of armature currents at frequency (fer) produces positive and negative rotating magnetic fields in the synchronous machine. The time distribution of the phase currents together with the space distribution of the armature windings causes positive and negative rotation at an angular electrical velocity of $2*\pi*f_{er}$. The frequency of rotor body currents induced by these fields is governed by the relative velocity between the armature and the rotor. Positive sequence components of stator current produce rotor currents at subsynchronous frequency $f_r = f_o - f_{er}$, Negative sequence components of stator current produce rotor current at super synchronous frequency $f_r = f_o + f_{er}$.

$$f_r = f_o \pm f_{er} \dots \dots (2)$$

Compared to the synchronous torques the subsynchronous generator torques visualized in the air gap are relatively small caused due to the rotor currents, hence dc rotor current can be assumed. As the constant rotor magnetic field overtakes the more slowly rotating subsynchronous mmf in the armature, a subsynchronous torque is produced having a frequency which is the difference between the frequency corresponding to rotor average velocity (f_o) and the electrical subsynchronous frequency (f_{er}). The subsynchronous electrical frequency and subsynchronous torque frequency are said to be complementary because when added the sum is equal to the synchronous frequency. [5]

B. Torsional Interaction

Torsional interaction is the phenomena between the mechanical system (turbine-generator) and a series capacitor compensated electrical network. Small disturbances lead to simultaneous excitation of all natural modes of the electrical and mechanical systems. The turbine-generator shaft system responds to disturbances with oscillations at its torsional natural frequencies. For the simplified system shown in Figure 1, the natural mechanical frequency, neglecting damping, is given by equation 3. Just as the electrical system, the real mechanical system is multimodal and will have more than one natural frequency.

$$f_n = \left[\frac{K_{12}}{\frac{M_1 * M_2}{M_1 + M_2}}\right]^{\frac{1}{2}} \dots \dots (3)$$

Oscillations of the generator rotor at this frequency result in modulation of the generator voltage. The subsynchronous frequency of voltage component is $f_{en} = f_0 - f_n$. When this frequency is close to the natural frequency of system, the resulting armature currents produce a magnetic field which is phased to produce a torque which reinforces the previously mentioned generator rotor oscillations. Due to the reduced damping because of aligned frequency the oscillations are grown or sustained. This phenomenon is known is called torsional interaction. [1]

C. Torque Amplification

By employing series capacitors the shaft stress is also be amplified during major transient events above the nominal stress level without employing series capacitors. Transient torque amplification becomes important only when the shaft resonances of a specific turbine-generator and the electrical resonances of the series-compensated transmission network are closely aligned. If such alignment are shown it may result in loss of life of the shaft. The transient torque magnitude should be measured during major transient events which are much more than those developed as a result of a three phase fault in an uncompensated line. [4][5]

D. SSR Caused by Feedwater Pumps Fed by Thyristor Cascades

The SSR detected in this case was by a torsional stress analyzer. The boiler feed-water pumps of this power plant were driven by power-converter-controlled asynchronous motors. With the turbine operating almost at full load, subsynchronous feedback from the converter cascade into the network caused pulsation in the electrical airgap torque of the generator of approx. 7% of rated torque and with a frequency of 16 Hz. This pulsation matched the first torsional frequency of the shaft system and excited torsional vibrations in the turbine generator. The pulsation was amplified by the oscillating generator rotor due to negative damping. Because these relatively small torsional vibrations were frequently induced, a high generator shaft life expenditure quickly accumulated, sparking off intensive investigations to find the cause of this torsional impact. [3]

E. ***Electro-Mechanical Resonance During Running up of a Squirrel Cage Induction Machine***

Using different types of drives to run induction machine can cause an electromechanical resonance during running up. The torque in the connection components between motor and main engine can reach values much bigger than the maximum stationary breakdown torque. This highly depends on the mechanical-geometrical and the electromechanical attributes of the entire system. The above phenomenon highly depends upon the mechanical damping of the system hence any predictions are hard to be made. [3]

F. ***SSR Caused by Slipring Machine with Faulty Rotor Windings***

In this case SSR caused by slip ring machines with faulty rotor windings closely connected to a generating system with presence of synchronous generator. In a plant for natural gas liquefaction some electrical machines were damaged at the same time. On the one hand the slip ring connection of a induction machine tore off. This caused an arc and one rotor winding got out of function. On the other hand the shear pins at the shaft of three synchronous generators which supplied the private net tore off at the same time. The cause was assumed that SSR occurred during the running up of the slip ring induction motor which caused the tear off of the shear pins within the generator shaft. [3]

G. Device Dependent SubSynchronous Oscillation

Subsynchronous oscillations in turbine-generators have also resulted from interaction with other power system components. Other potential sources include power system stabilizers, high voltage DC converter controls, static var compensator, high speed governor controls, and variable speed drive converters. In general, any device that controls or responds rapidly to power or speed variations in the subsynchronous frequency range is a potential source for excitation of subsynchronous oscillations. [1]

H. ***HVDC Converter Controls***

HVDC converters generate currents in a wide band of frequencies. Therefore, HVDC converters can excite torsional modes of turbine-generators through constant DC power, current, or voltage control loops and/or the auxiliary power control loop used to enhance the stability of low frequency (0.1-2.0 Hz) oscillations of the interconnected AC system. Modifications to converter controllers or addition of a supplementary subsynchronous damping control (SSDC) to the current controller may eliminate this problem.

I. G. Speed Governor System

The control action of electro-hydraulic governors can excite turbine-generators into subsynchronous oscillations. This is because their bandwidth can be wide enough to pass the torsional frequencies to the turbines, providing a closed loop for subsynchronous oscillatory modes. Conventional hydraulic governors do not excite torsionals.

III. Problem Identification

Problem identification usually begins with SSR studies based on estimated machine parameters. Parameter sensitivity studies are essential to determine the need for SSR tests. Special SSR testing can provide refined parameters. Results from the studies and tests are employed to define appropriate countermeasures. The analyses should identify the most probable and the most severe problems for all stages of generation and transmission system development. [1]

Analytical Tools

Several analytical tools are available for studying SSR problems. These tools are generally in the form of digital computer programs. The widely used techniques for SSR analysis are: frequency scan, eigenvalue, and digital time domain simulation. Other techniques have been developed and published in the literature.

1. Frequency Scan Technique

Results of frequency scanning studies aid in identifying potential induction generator effect, torsional interaction and transient torque amplification problems. The frequency scan technique determines the system impedance, as a function of frequency, viewed from the neutral of the generator under study. This impedance, in conjunction with machine mechanical parameters, can be used to estimate negative damping for the active machine torsional modes. This is an approximate linear method used to screen system conditions that are potential SSR problems and identify those parts of the system that do not influence the SSR phenomenon. This program is cost-effective as a screening tool.

2. Eigenvalue Technique

Eigenvalue techniques are based on the mathematical model of the system using its set of linearized differential equations. They are used to examine the effect of different series compensation levels and system configurations on the damping of torsional modes. Combined with well known linear control theories, eigenvalue studies can be used to design controllers of SSR countermeasures. Eigenvalue studies can also be used to map constant damping contours for varying compensation levels of multiple transmission lines.

Although eigenvalue techniques are extensively used in SSR analysis, they suffer from several shortcomings:

- The results are valid only for small perturbations, so, they cannot be used to study torque amplification problems.
- Positive sequence representation with limited system representation.
- Physical nonlinearities, e.g., magnetic saturation of generators, cannot be easily included in the system model.
- Switching devices, e.g., thyristor valves, are represented by approximated linear transfer functions which neglect the possible impact of switching on the system behavior. [1]

IV. MITIGATION TECHNIQUES

1. Reduced Compensation Level & Operating Procedures

SSR can be avoided by limiting the total amount of series compensation installed on transmission lines radially connected near to T-Gs. However, the level of series compensation is often selected based on system performance requirements and reducing the level of installed series compensation could result in constrained system operation or the need for new transmission.

The amount of installed compensation can also be limited by adjusting net amount of series compensation during its operation by bypassing capacitor segments. This helps in changing the resonant frequency of electrical line which may match with the mechanical system. During light load conditions and consequently low damping, SSR risk is greatest.

The limits on series compensation can be developed on the basis of analytical studies and measurements on turbine-generator torsional vibration modes. This method of mitigation can be effective for avoiding both SSR stability and transient torque amplification problems. However, for many series capacitor applications, reducing the amount of compensation is not feasible due to system performance requirements. Under these conditions, mitigation at the generator or the series capacitor may be required. [4]

2. Passive SSR Blocking Filters at the Generator

Filters are employed near the affected generator which blocks the currents at SSR frequencies flowing through the generator step-up transformer neutral connections to ground. SSR blocking filters can eliminate both SSR stability and transient torque amplification problems over a very wide range. Hence the need to limit series compensation is also eliminated. [4]

3. Thyristor Controlled Series Compensation (TCSC)

Thyristor controlled series capacitors can be effective in mitigating SSR. In a TCSC, thryistor valves are gated to control the current through the capacitor, thereby affecting the dynamic characteristics of the series capacitor at subsynchronous frequencies. If the control system is properly designed and tuned, the TCSC can reduce the natural tendency of the series capacitor to resonate with the inductance of the transmission system, and consequently reduce the detrimental impact of SSR on nearby turbine generators.

One attractive aspect of using TCSC for SSR mitigation is that TCSC mitigates the electrical resonance at its source – the series capacitor. All nearby turbine-generators benefit from the mitigating effects. However, the beneficial effect on SSR is highly dependent on the TCSC control system, and a few cautions to this approach are listed below:

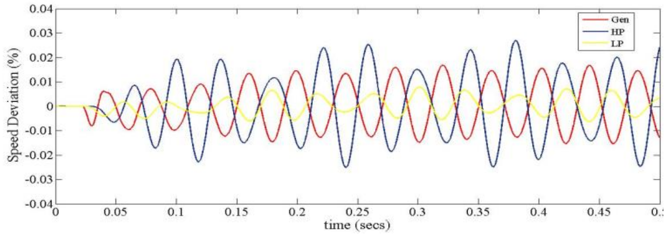
- Thyristor valves do not inherently mitigate SSR. Sophisticated control algorithms are required, and the algorithms must be precisely tuned to achieve desired SSR mitigation objectives. A small change in tuning can have a large effect on SSR, and can even change a stable operating point to an unstable operating point. This is of particular concern when the TCSC control system requires maintenance for reasons not related to SSR.

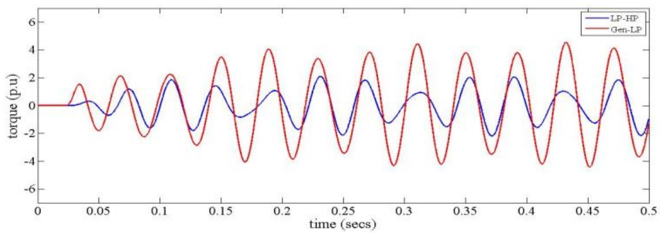
- Control tuning is sensitive to the power grid. If the power grid experiences significant changes in the future, it may be necessary to re-tune the control system to retain the SSR mitigation qualities of the TCSC.

- TCSC can mitigate SSR instabilities, but not transient torque amplification. If a system suffers from transient torque amplification, another form of SSR mitigation may be required. [4]

4. Dynamic Torque Stabilizer

Since the damping matrix of a steel shaft system is more or less a fixed parameter, the development of the torque stabilizer was based on applying an additional electromagnetic torque through the stator winding, thus causing the same effect as one (or more) increased damping coefficient(s). In order to damp only one natural frequency of a shaft assembly, this can be realised in applying an electromagnetic torque in counter-phase to the measured torsional velocity of the shaft by means of the arrangement shown in Fig. The torsional velocity is electronically derived from a torque sensor measurement in the block "Control System for Signal Modification". The mechanical torque measurement is performed with a sensor especially suited for measurements on medium or large diameter shaft lines. The damping converter also is a current controlled 6-pulse thyristor bridge. Its current reference consists of a DC component and an alternating component. The DC component is important because it enables to operate the inductor in the DC circuit as buffer storage of magnetic energy, being loaded and unloaded in counter-phase to the torsional velocity of the shaft at the location of the torque sensor. Since the torque stabilizer generates electromagnetic torque acting on the rotor with a frequency





corresponding to the resonant frequency, this damping method is very efficient. [6]

V. Modelling & Simulation

1. System Configuration

The system here considered is the IEEE second benchmark model of which the single line diagram and data used in this study are shown in Figure 3 where a single generator of 600 MVA, 22kV is connected to infinite busbar through transformer and two transmission lines. One line is series compensated with three different levels of series capacitive compensation (20%, 55% and 90%).

A transient disturbance is applied at t=0.02sec and removed after 0.017 is a three-phase to graound phault. The generator spring-mass consists of three masses the generator, LP & HP turbines. The model is constructed in MATLAB conjuction with Simulink.

Both the electrical network and the spring-mass system are represented in Matlab in their differential equations, linearised about an operating point (Bus1) and arranged in state space for analysis and simulation purposes. Figure 2 shows the Matlab representation of the second benchmark system. [2]

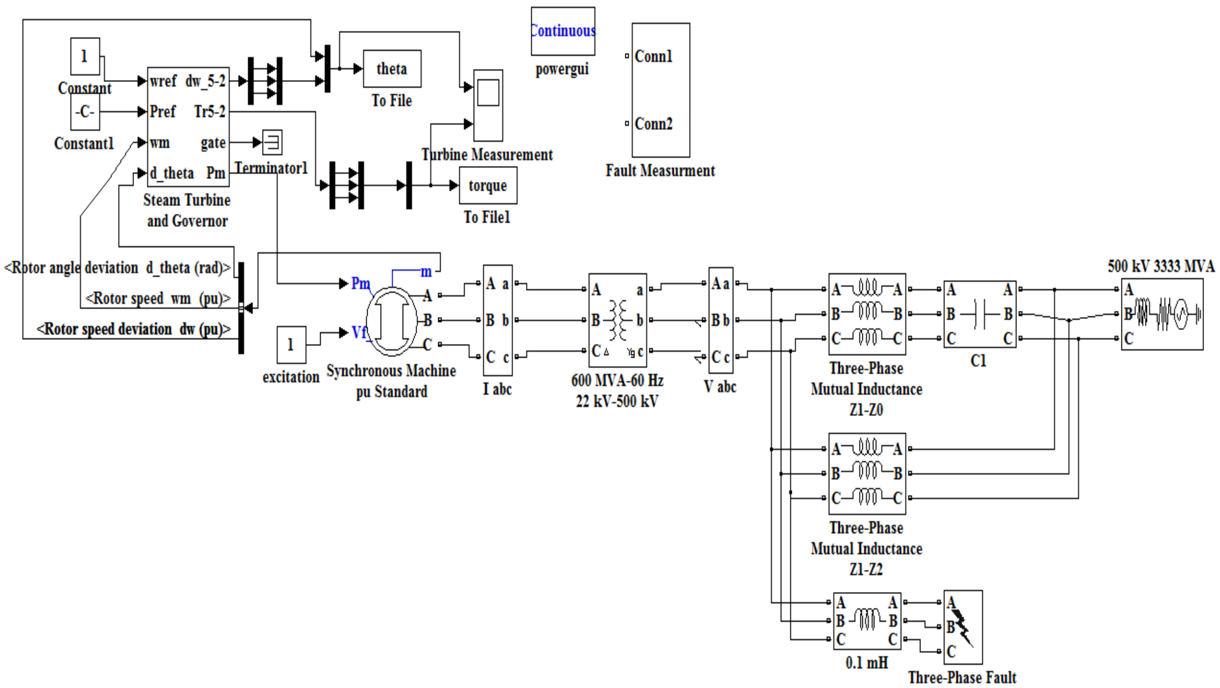


Figure-2 Matlab representation of SSR model

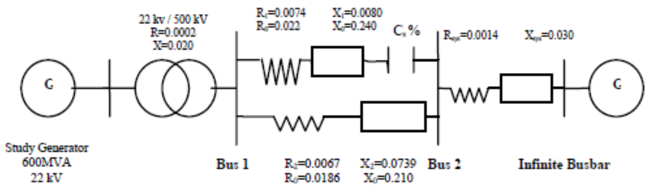


Figure-3 Single line diagram of the casestudy

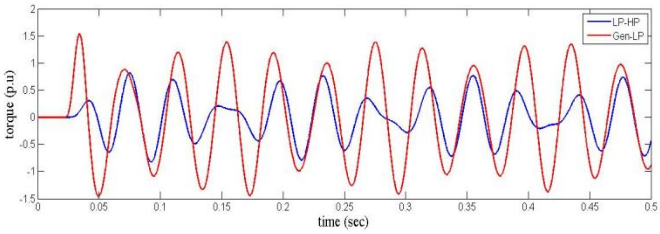


Figure-4

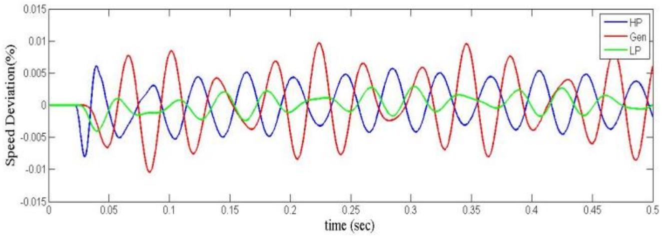


Figure-5

Table-1 The right-hand eigenvectors for eigenvalues No. 8 and 10

State variables of the electrical network	Right hand eigenvector for Eigenvector No. 8	Right hand eigenvector for Eigenvector No. 10
Uc_Cs 55%/Cs = 55%/Series RLC Branch1	0.22199+0.77801i	-0.79864-0.20136i
Uc_Cs 55%/Cs = 55%/Series RLC Branch2	0.22199+0.77801i	0.39905+0.10054i
Uc_Cs 55%/Cs = 55%/Series RLC Branch3	0.22199+0.77801i	0.3996+0.10082i
IL_winding1 Z1-Z0/Mutual Inductance	0.00015687+0.00054979i	-0.00064347+0.0039488i
IL_winding2 Z1-Z0/Mutual Inductance	0.00015687+0.00054979i	0.00032116-0.001973i
IL_winding3 Z1-Z0/Mutual Inductance	0.00015687+0.00054979i	0.00032231-0.0019758i
IL_winding1 Z1-Z0/Mutual Inductance	-0.038773-0.13589i	-0.00064347+0.0039488i
IL_winding2 Z1-Z0/Mutual Inductance	-0.038773-0.13589i	0.00032116-0.001973i
IL_winding3 Z1-Z0/Mutual Inductance	-0.038773-0.13589i	0.00032231-0.0019758i
IL_600MVA-60 Hz 22 kV-500 kV	0.038616+0.13534i	6.8498e-007+3.8137e-006i
IL_600MVA-60 Hz 22 kV-500 kV	-1.3037e-008-4.5693e-008i	-1.5145e-005+4.3989e-005i
IL_600MVA-60 Hz 22 kV-500 kV	0.038616+0.13534i	-3.4256e-007-1.9054e-006i
IL_600MVA-60 Hz 22 kV-500 kV	-1.3037e-008-4.5693e-008i	7.5633e-006-2.1979e-005i
IL_600MVA-60 Hz 22 kV-500 kV	0.038616+0.13534i	-3.4241e-007-1.9083e-006i
IL_600MVA-60 Hz 22 kV-500 kV	-1.3037e-008-4.5693e-008i	7.582e-006-2.2009e-005i

2. *SSR Analysis by Eigenvalue Technique*

There is a need to verify subsynchronous conditions severity and the distribution of these conditions between system's state variables. This can be accurately accomplished using eigenvalue analysis, which can be easily performed using Matlab control system toolbox. Table 1 shows eigenvalue of the electrical network for different levels of compensations, where the imaginary part indicates the frequencies of the oscillatory modes, while the real part represents the damping factor of these modes. For stable conditions all eigenvalues must be at the left of imaginary axis. If the locus of a particular eigenvalue approach or cross the imaginary axis, then a critical conditions is identified that requires the application of one or more countermeasure.

In addition, the state variables that have important role to contribute to a given mode of oscillation are identified using eigenvectors. This often tells the engineer exactly those variables that need to be controlled in order to damp a subsynchronous oscillation. Table 1 shows the right-hand eigenvectors for eigenvalues No. 8 and 10 for 55% level of compensation, where U_Cs% is the voltage across the series capacitor and IL is the current through an inductor.

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3. *Simulation*

This program uses step-by-step numerical integration to solve set of differential equations representing the overall system under study. Power System Blockset allows detailed modeling of machines and network as well as circuit breakers action and transient faults.

Figures 4 and 5 show the effect of series compensation level on the magnitude of the torque oscillation between Gen and LP turbine and between LP and HP turbine. For every case of compensation the fault clearing time is 0.017 sec. The magnitudes of the torques is evidenced when the compensation level is changed from 20% to 55%.

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