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Transient Performance Of A Series Compensated Transmission System

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Abstract:

There are many different methods used to improve the stability of power systems. One of them is series compensation; it is the use of capacitance in series with the transmission lines. The addition of capacitance serves multiple purposes the most important being the improvement in the stability along the entire line and they are also found on long transmission lines used to improve voltage regulation. The series capacitors are provided with modern capacitor protection techniques Metal Oxide Varistors (MOV) to protect from high voltages that would be seen across their terminals when there is a faulty condition (very high currents).

Transient tests are to be performed on the model of power system for desired load flow and to obtain a steady state. For some faults, the transient performance of the system is analyzed. One of the major and hazardous disadvantage of series compensation is Sub-synchronous Resonance is considered and analyzed for various degrees of compensation.

In our project, we have built the simulations of the above mentioned systems and their transient performances are thoroughly analyzed and developed using MATLAB 7.0.1 and also using SIMULINK. The reason for choosing MATLAB is, it is a high-performance language for technical computing.

1.Introduction

Worldwide transmission systems are undergoing continuous changes and restructuring. Transmission systems must be flexible to react to more diverse generation and load patterns. In addition, the economical utilization of transmission system assets is of vital importance to enable electric utilities in industrialized countries to remain competitive and to survive. In developing countries, the optimized use of transmission system investments is also important to support industry, create employment, and efficiently utilize the scarce economic resources. There are many different methods to improve the stability of power systems. Some of these methods include reducing generator and transformer reactance, increasing the number of parallel lines used, using Shunt and Series Compensation.

Series Compensation is a well-established technology, which reduces transmission reactance at power frequency and brings a number of benefits for the user of the electrical grid, all contributing to an increase of the power transmission capability of new as well as existing transmission lines. The recent incorporation of thyristor control has enabled further flexibility of series compensation, adding useful new applications, such as improved steady-state and transient stability limits, reduced capacitor size and weight, and decreased space requirements for capacitor installation. As a result, the use of this technology has been receiving increased interest in the search of optimizing the series compensation in a cost-effective manner.

2.Series Compensation and its need

Series Compensation has many advantages over Shunt Compensation, as well as some disadvantages.

Advantages of Series Compensation include:

- Increases Power Transfer of existing lines.
- Voltage Regulation.
- Reactive Power balance.
- Raises transient stability.

Disadvantages of Series Compensation include:

- High Initial Cost.
- Problem of capacitor damage during fault conditions.
- Past reinsertion problems following a disturbance

- Sub-synchronous Resonance.

3 Protection Techniques

Protection is much more important in series compensation than in shunt. The main reason for this is fact that the capacitors are placed in series with the line thus making the device more susceptible to line currents than shunt capacitors. This need for additional protection is one of the main reasons that series compensation is more costly than shunt compensation. One of the main disadvantages in using series capacitor is during the fault condition there is high reverse voltage impressed across the terminals of the capacitor, which in turn may damage the capacitor and may demand replacement. To protect this capacitor from this type of damage a special technique incorporating a Metal Oxide Varistor (MOV) for the protection of capacitor. Approximately 40-50% of the total cost of a series compensation installation goes to system protection. Fixed Series Capacitor over voltage protection is based on 3 techniques:

- MOV protection.
- MOV with a forced triggered bypass gaps.
- SCR valve bypass.

The MOV with a forced triggered bypass gaps is further classified into:

- Single Segment Protection Scheme
- Dual Segment Protection Scheme

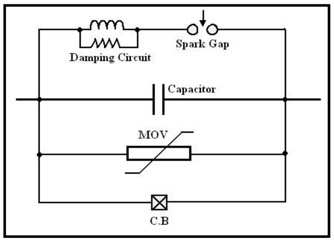


Figure 1: Single Segment Protection Scheme

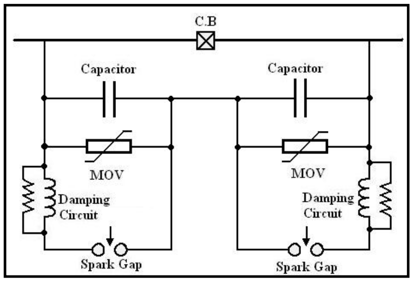


Figure 2: Dual Segment Protection Scheme

3.1 Fuse Protection

Fuses are used to disconnect and isolate the faulted section of a capacitor bank. By separating the capacitors into sections and protecting each section by a different fuse, the risk of secondary faults can be eliminated..

4.Transmission Network And Other Limitations

4.1.Transmission Network In A Power System

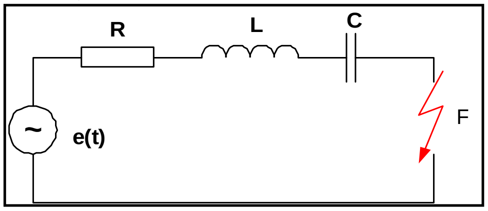
Electric power transmission, a process in the delivery of electricity to consumers, is the bulk transfer of electrical power. Typically, power transmission is between the power plant and a substation near a populated area. Due to the large amount of power involved, transmission normally takes place at high voltage (110 kV or above). Electricity is usually transmitted over long distance through overhead power transmission lines. Underground power transmission is used only in densely populated areas due to its high cost of installation and maintenance, and because the high reactive power produces large charging currents and difficulties in voltage management.

4.1.1 Limitations In The Transmission System

The amount of power that can be sent over a transmission line is limited. The origins of the limits vary depending on the length of the line. For a short line, the heating of conductors due to line losses sets a "thermal" limit. If too much current is drawn, conductors may sag too close to the ground, or conductors and equipment may be damaged by overheating. For intermediate-length lines on the order of 100 km (60 miles), the limit is set by the voltage drop in the line. For longer AC lines, system stability sets the limit to the power that can be transferred. Approximately, the power flowing over an AC line is proportional to the sine of the phase angle between the receiving and transmitting ends. Since this angle varies depending on system loading and generation, it is undesirable for the angle to approach 90 degrees.

4.1.2.Analytical Expressions Of Fault Currents In Inductive And Series Compensated Networks

Transmission lines are inherently inductive. In a network without series capacitors, fault currents are inductive in character and the line current always lags the voltage by some angle. With the series compensation of the transmission lines, capacitive elements are introduced and the resulting network is no longer only inductive under all fault conditions. The degree of this change depends on the line and network parameters, the extent of series compensation, the type of fault, and the fault location. We will use the reduced and simplified network shown in *Figure*.3:



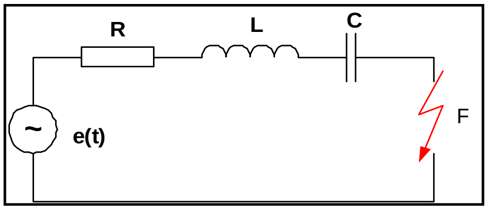


Figure3: Simplified representation of a fault in a series compensated network

We assume that the fault occurs at t = 0 and that λ is the fault inceptionangle. Equation 1 defines the source EMF:

$$e(t)=E_m \cdot \sin(\omega \cdot t+\lambda)$$ Equation 1

Equation 2 gives the voltage relations for the non-series-compensated line:

$$L\frac{di_f}{dt}+R \cdot i_f(t)=E_m \cdot \sin(\omega \cdot t+\lambda)$$ Equation 2

Equation 33 define the fault current if (t) for the non-series-compensated line:

$$i_f(t)=i_{fs}(t)+i_{ft}(t)$$ Equation 3

Here $i_{fs}(t)$ is the steady-state part of the fault current and $i_{ft}(t)$ is the transient part. Equation 4, **Error! Reference source not found.**5, and **Error! Reference source not found.**6 define the steady-state part of the fault current:

$$i_{fs}(t)=\frac{E_m}{Z} \cdot \sin(\omega \cdot t+\lambda-\phi)$$ Equation 4

the transient part of the fault current:

$$i_{ft}(t)=K_0 \cdot e^{-\frac{t}{L/R}}$$ Equation 5

the voltage loop for the series compensated line:

$$L\frac{d^2 i_f}{dt^2}+R\frac{di_f}{dt}+\frac{1}{C}i_f(t)=E_m\cdot\omega\cdot\cos(\omega\cdot t+\lambda)$$ Equation 6

the fault current i_f (t) in the series compensated line:

$$i_f(t)=i_{fs}(t)+i_{ft}(t)$$

Equation 7

Here i_{fs} (t) [A] is the steady-state part and i_{ft} (t) [A] is the transient part of the fault current. Equation 1, **Error! Reference source not found.**2, and **Error! Reference source not found.**13 define the steady-state part of the fault current:

$$i_{fs}(t)=\frac{E_m}{Z}\cdot\sin(\omega\cdot t+\lambda-\theta)$$ Equation 8

the transient part of the fault current:

$$i_{ft}(t)=e^{-\alpha\cdot t}\left(K_1\cdot\cos(\beta\cdot t)+K_2\cdot\sin(\beta\cdot t)\right)$$ Equation 9

Here $I_{t=0}$ is the current through the inductance at t = 0, and $V_{t=0}$ is the voltage across the capacitor at t = 0. The fault current for a fault in a series compensated network consists of a steady-state part and a transient part. The transient part consists of a damped oscillation. The latter has an angular frequency β and dies out with a time-constant of 1/α . This oscillating transient part corresponds to the DC transient part in a non-compensated network.

4.2.Sub Synchronous Resonance Risk On Turbine Generators

Application of series capacitors in long electric power transmission lines is a cost-effective method to increase power transfer. However, use of series capacitors has sometimes been limited because of the concerns for sub synchronous resonance (SSR), a detrimental interaction between series capacitors and nearby turbine-generators. With today's understanding of the SSR phenomenon and proven methods for SSR mitigation and protection, series capacitors can be applied while effectively managing the risks associated with SSR.

The series compensated transmission lines have line inductance, resistance and series capacitance which result in electrical resonant frequencies (f_e) below the fundamental power frequency Resonant frequencies below the fundamental frequency are called sub synchronous. If the transmission line resonant frequency, f_e, is close to the complementary mechanical system frequency ($60-f_m$) of the generating machine, then the two oscillatory systems can interact with each other. In some operating conditions, the interaction can result in damaging shaft torques on a turbine-generator shaft. This interaction is called SSR, and it occurs because of the interchange of energy between the series capacitors on the transmission lines and the mass-spring system of the turbine-generator shaft. This interchange occurs at the sub synchronous resonance frequency by modulating the 60 Hz wave form.

Shaft torques due to SSR is caused by two types of interaction mechanisms; SSR instability and SSR transient torque amplification.

4.2.1 SSR Instability

Series capacitor compensation has a tendency to act as a negative damping on torsional vibrations of nearby turbine generator units. When this negative damping effect overcomes the inherent mechanical damping of one of the shaft torsional vibration modes, the vibration will grow exponentially and lead to damage on a shaft. Generally, such growth in shaft torsional vibrations occurs with a long time constant on the order of many seconds. This Torsional interaction with the negative damping effect becomes unstable and excessive if the electrical and torsional resonance frequencies nearly coincide as fundamental frequency (50/60 Hz) complements and if the inherent mechanical damping is lower than the negative damping effect of series capacitor.

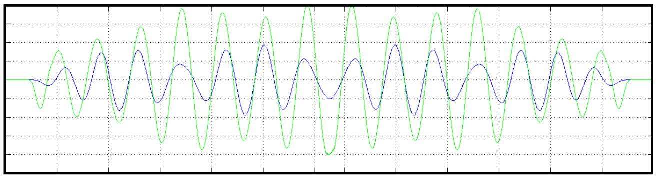


Figure.4: SSR Instability showing shaft torques on generator-exciter Shaft

Error! Reference source not found.4 show the growth of torques from a simulation of a SSR instability event. The shaft torque on the critical shaft (generator-exciter) reaches about .08 per unit in 1.6 seconds. For this shaft, the endurance torque level where significant fatigue life expenditure starts to occur is about 0.36 per unit. The slow growth of torques in this case enables adequate time to trip a transmission line, bypass series capacitors, or trip the turbine-generator to prevent damage to the shaft. This type of SSR instability phenomenon resulted in shaft failure on the Mohave turbine-generators in the early 1970's.

4.3.Transient Torque Amplification

Series capacitors also have a tendency to amplify the shaft stress during major network transient events over above the stress level that would exist without the series capacitors. The transient torque on the turbine-generator shaft should be evaluated as well as the resulting loss of life of the shaft due to the cumulative fatigue. The critical measure of the transient torque is the magnitude of the shaft vibration excited during each network transient event typically lasting on the order of one second. Figure8 shows an example of SSR transient torque amplification where the resulting shaft torques are higher with 70% series compensation than with 60%. The electrical torque and HP-IP shaft torque are shown. Transient torque amplification becomes important only when the generator becomes nearly radial on lines that are heavily compensated with series capacitors.

A solution is to limit the voltage across the series capacitor with metal-oxide varistors or protective gaps and hence to reduce the transient energy involved in the transient torque amplification. An alternative solution is to block the SSR current from flowing into a generator.

A similar type of shaft torque amplification can occur with automatic high speed reclosing of transmission lines. Reclosing (particularly when the fault still exists) can result in a second electrical torque stimulus to the shaft system, that dependent upon timing, can increase the torsional oscillations which have not decayed sufficiently from the first fault clearing. While indiscriminant three-phase reclosing would be the worst reclosing practice, single-pole reclosing can also provide extra torsional stimulus.

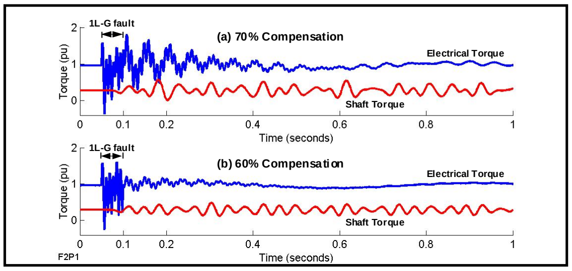


Figure 5: Subsynchronous Resonance Transient Torque Amplification

4.3.1.SSR Mitigation And Protection

Numerous methods for mitigating SSR have been developed and implemented. The type of mitigation selected for a particular application depends on the severity of the SSR, the performance required, and economics. System studies are performed to quantify the level of SSR and to develop appropriate mitigation and protection schemes.
Few appropriate mitigation and protection schemes:
1.passive SSR blocking filters were installed to block the currents at SSR frequencies .
2. Also supplemental excitation damping controls (SEDCs) were installed to provide damping at the SSR frequencies. 3.Presently, the rotating exciters on the units are being replaced with bus-fed excitation systems, and the SSR mitigation and protection schemes are being upgraded.

5.Simulation Block Diagrams And Simulation Results

5.1.Description Of The Network

The single-line diagram shown here 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 split into two 300 km lines connected between buses B1, B2, and B3.

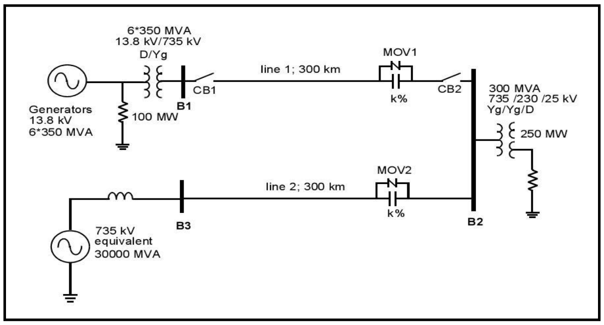


Figure 6: Series Compensated Transmission System

To increase the transmission capacity, each line is series compensated by capacitors representing k% of the line reactance. The series compensation equipment is located at the B2 substation where a 300 MVA-735/230 kV transformer feeds a 230 kV-250 MW load. Each series compensation bank is protected by metal-oxide varistors (MOV1 and MOV2). The two circuit breakers of line 1 are shown as CB1 and CB2.Here k is the degree of compensation (X_C/X) i.e., the ratio of capacitive reactance to the total reactance of the line.

5.2.Transient Response of Series Compensated System with MOV Protection

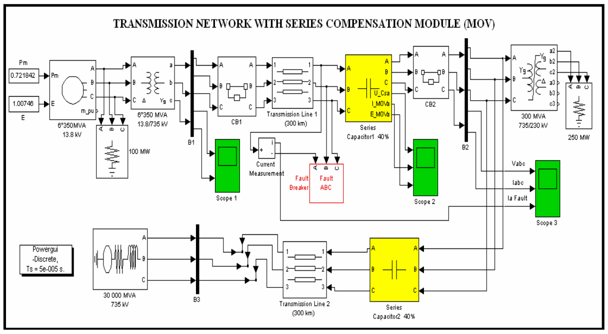
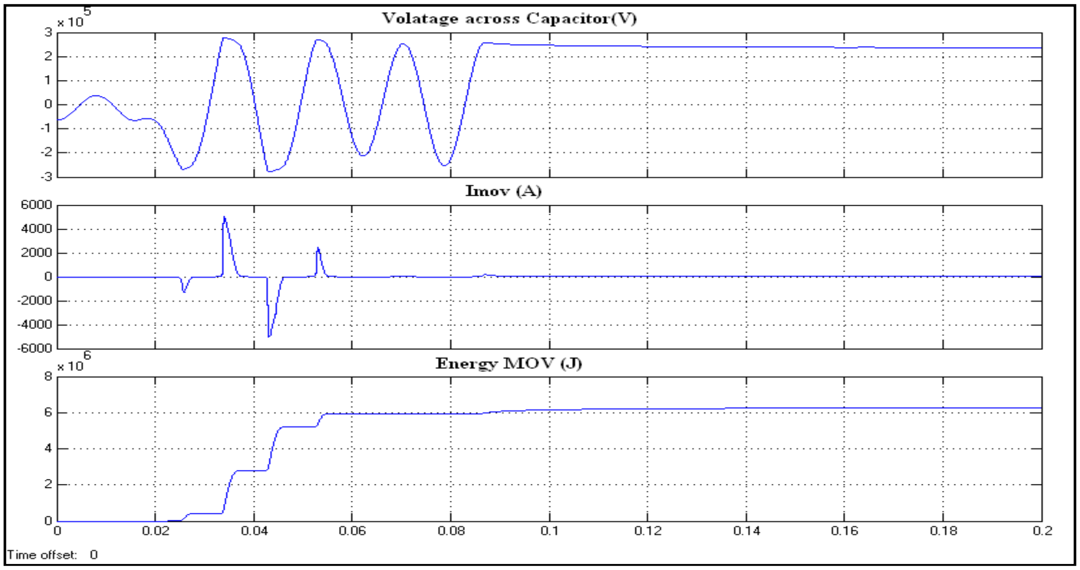


Figure.7: Series Compensated Transmission System with MOV Protection

5.3 Transient Response

Simulation Results for a Line-to-Ground Fault for 40% compensation



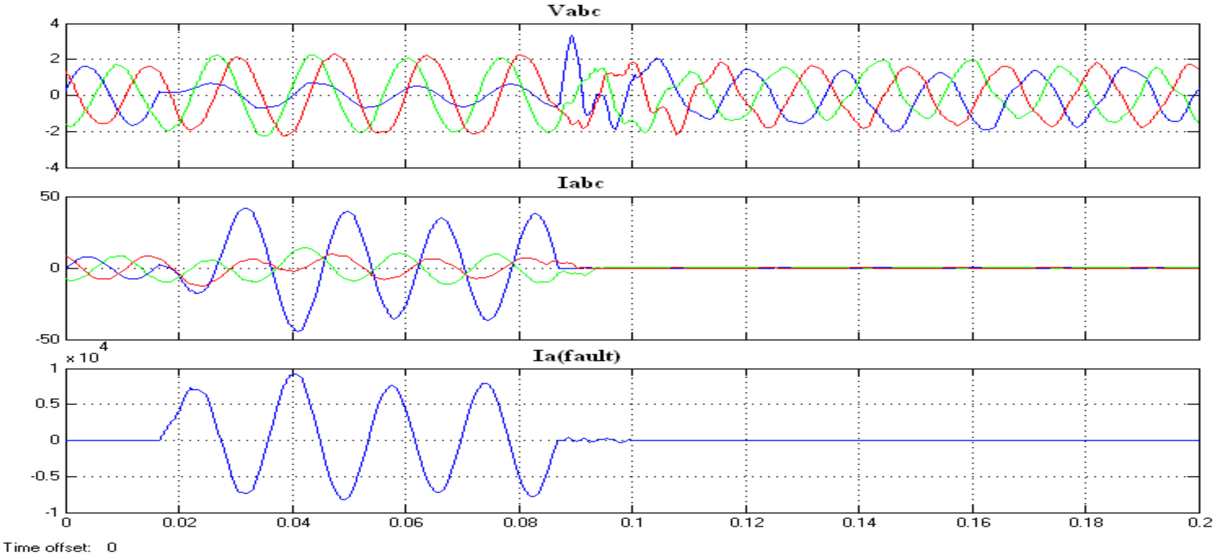


Figure 8 (a), (b): Response of System for Line-to-Ground Fault for 40% Compensation Level

5.4.Subsynchronous Resonance Analysis

The existence of the sub synchronous mode in the study system can be identified by frequency domain calculation of network impedance at bus 1. The impedance of the network as function of frequency is computed for different compensation levels.

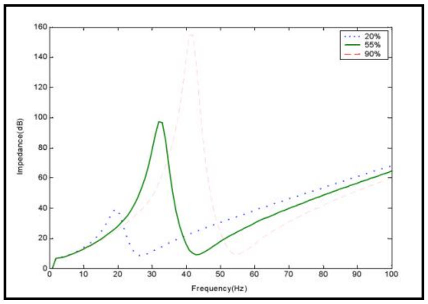


Figure 9: Impedance as the Network function of Frequency

From the network's frequency spectrum shown in figure 3, the natural frequencies (f_{er}) due to parallel resonance are clearly identified for each level of compensation suggested. These frequencies appear to the generator rotor as modulations of the fundamental frequency of the network (60 Hz), giving sub synchronous frequencies ($f_{or} = f_o - f_{er}$). If these frequencies are close to one of the mechanical natural frequencies of the spring-mass system, the turbine –generator shaft might experience torsional modes of oscillations that will cause possible fatigue and damage.

5.5.Steam Turbine And Governor Mechanism For Torque Amplification Study

In this model, a Steam Turbine and Governor Model for Torque Amplification studies and also the Speed Deviations in it. The power system network consists of transmission line with Series capacitor connected in series with the line. It also had a Delta/Star connected transformer in the line. The star end of the transformer is grounded with a reactance of 0.1mH. A fault is created for 0.2 seconds and it is lasted for 0.017 seconds.

The Scope Block named “Turbine” gives the Speed Deviations of Generator(), Low Pressure Turbine () and High Pressure Turbine () and the Torques transmitted between shaft’s masses Generator-Low Pressure Turbine (T3) and Low Pressure Turbine-High Pressure Turbine (T2). The Scope block named “I_falut” gives the fault current induced in the network. The Scope block named “Capacitor Voltage” gives the voltage across the capacitor. A peak torque of over 4 p.u. is observed between masses 1 and 2. The frequency of the oscillations observed in the torques and speed deviations is about 27 Hz.

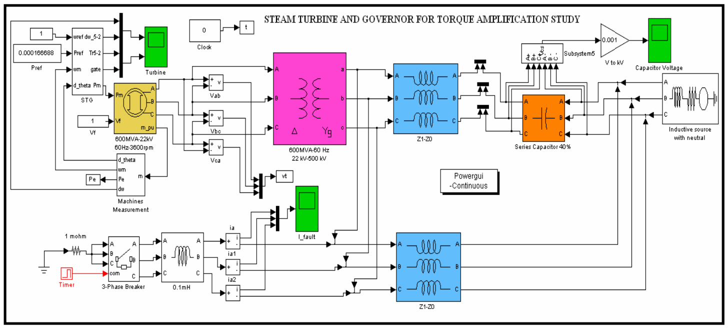


Figure 10: Steam Turbine and Governor System for Torque Amplification Study

speed Deviations and Torques transmitted between shaft's masses for 40% compensation and Fault clearing time of 17msec

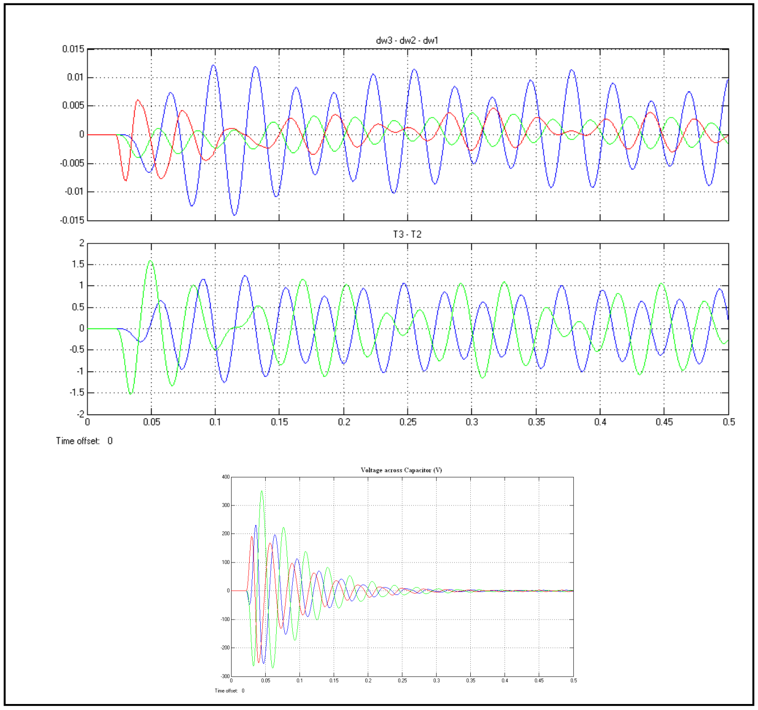


Figure11 (a),(b): Speed Deviations and Torques Transmitted in the System for a Fault for 40% Compensation Level

6.Conclusion

Series capacitors can significantly increase the power transfer capability of ac transmission systems. However, in some applications, series capacitors may introduce detrimental side effects, including SSR and transient torque amplification.

Several proven methods exist for mitigating the effects of SSR, including:

- SSR blocking filters
- Supplemental exciter damping controls (SEDC)
- Thyristor-controlled series capacitor (TCSC)
- Dynamic stabilizer at generator
- Switching of series capacitor segments
- Limiting the total amount of compensation to a tolerable level

In addition, torsional relays are used to protect turbine-generators from damage in the event that mitigations fail or unanticipated system events occur. From the results presented in this project, it is clearly observed that the network frequencies depend on series compensation level. Further, the fault clearing time has a significant role in the dynamic behavior of the system. From such investigation as in this project, Planners will be able to establish acceptable series compensation levels and switching arrangements for a specific stage of system design and development taking into account power quality and system’s reliability. The existence of sub synchronous conditions and their severity can be verified using Matlab and PSB as a simulation and analytical tool.

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