EFFECTS OF PERCENTAGE OF SERIES COMPENSATION ON SUBSYNCHRONOUS RESONANCE MODES OF POWER SYSTEM [+]

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Abstract :

Series compensated power system may lead to a very unusual problem known as SubSynchronous Resonance (SSR) which adversely affects the system stability and under certain operating conditions may result in fatigue breakdown of the turbine – generator shafts. This paper investigates the effects of variation of percentage of series compensation of the transmission line reactance on the excited subsynchronous resonance modes in power transmission system, and these excited modes are calculated for different values of compensation after a three- cycle, three- phase to ground fault incidence at bus bar (B_2) of the power system which has been modeled and simulated in Mat-lab/Simulink software.

Keywords: subsynchronous resonance, series capacitor, torsional interaction.

تأثير النسبة المئوية للتعويض نوع التوالي على الترددات الرنينية تحت التزامنية لمنظومة القدرة

عادل رضا عثمان

المستخلص :

منظومة القدره التى تم تعويضها بمتسعه على التوالى يمكن ان تؤدى الى حدوث مشاكل غير مؤلوفه تعرف بالرنين التحت التزامنى والذى يؤثر على استقرارية المنظومه و فى حالات تشغيليه محدده يمكن ان تؤدى الى كسر الجزء الرابط بين المولد و التوربابن. فى هذا البحث تم دراسة تغيير النسبه المؤيه للتعويض على قيم الترددات الرنينيه المثاره وحساب قيم هذه الترددات لقيم مختلفه من التعويض فى حالة منظومة قدره تتعرض الى عطل ثلاثى الطور الى الارضى و لمدة ثلاث دورات من التردد التزامنى لمنظومة القدره والذى تم محاكاته باستعمال برنامج الماتلاب.

1. Introduction :

SubSynchronous resonance (SSR) in power systems with capacitor compensated long transmission lines have drawn attention of power engineers since the two shaft failures at Mohave power station in 1970 and 1971 [1]. As well known, the SSR phenomena manifests itself in two forms: Self Excitation and Tortional Interaction. It arises because a disturbance in a compensated power system set up subsenchronous frequency currents corresponding to capacitor inductor combination [2]. To these subsynchronous frequency currents, the generator appears to be an induction generator since the rotor (field structure) is moving more

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rapidly than the rotating mmf caused by the subsynchronous frequency currents [3]. These currents result in the production of subsynchronous terminal voltage components which in turn sustain these currents. Since the slip to the subsynchronous frequency currents is negative, the rotor resistance viewed from armature terminals is negative. This phenomena due to induction generator effect is known as self-Excitation. Alternatively, it is also possible for a bilateral coupling to exist between the mechanical tortional modes of the turbine generator shaft and the natural modes of the electrical network [4]. The manifestation of SSR due to interplay between the electrical and mechanical networks is called as Tortional Interaction [5]. The SSR concern has lead to the approach of limiting the amount of series compensation in transmission lines to the order of 30-35% of system reactance [6]. A system may benefit from a higher level of compensation; however this is avoided as transmission system operators are concerned about the negative impacts of SSR [7]. This paper investigates the effects of variation of percentage of series compensation of the transmission line reactance on the excited subsynchronous resonance modes in power transmission system, and these excited modes are calculated for different values of compensation after a three- cycle, three-phase to ground fault incidence at bus bar (B_2) of the power system which has been modeled and simulated in Mat-lab/Simulink software.

2. line Compensation :

On long transmission lines, light loads appreciably less than Surge Impedance Loading SIL result in a rise of voltage at the receiving end, and heavy loads appreciably greater than SIL will produce a large dip in voltage. Shunt reactors are widely used to reduce high voltages under light load or open line conditions. If the transmission system is heavily loaded, shunt capacitors, static var control, and synchronous motos are used to improve voltage, increase power transfer, and improve the system stability.

2.1. Shunt Reactors :

Shunt reactors are applied to compensate for the undesirable voltage effects associated with line capacitance. Figure 1 shows the shunt reactor compensation. The amount of reactor compensation required on a transmission line to maintain the receiving end voltage at a specified value can be obtained as follows

For $V_S = V_R$ the required inductor reactance (X_{Lsh}) is

$$X_{Lsh} = \frac{\sin \beta \ell}{1 - \cos \beta \ell} Z_c \qquad \text{.............................(1)}$$

Where

β is the phase constant measured in radian per unit length

ℓ is the unit length

Z_c is the characteristic impedance

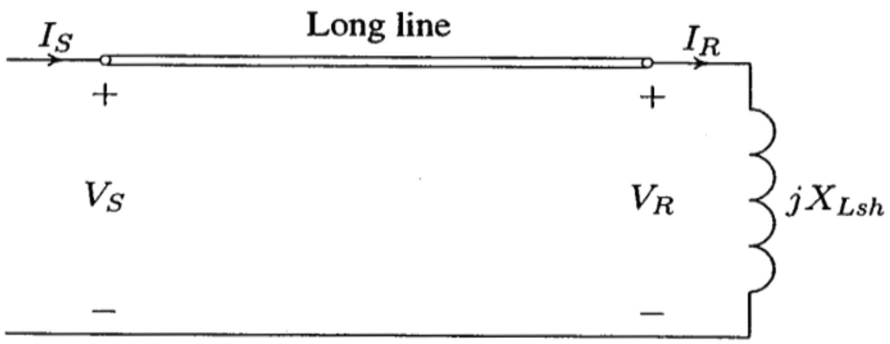


Figure (1): Shunt Reactor Compensation[8]

2.2. Shunt Capacitor Compensation :

Shunt capacitors are used for lagging power factor circuits created by heavy loads. The effect is to supply the requisite reactive power to maintain the receiving end voltage at a satisfactory level. Capacitors are connected either directly to a bus bar or to the tertiary winding of a main transformer and are disposed along the route to minimize the losses and voltage drops.

2.3. Series Capacitor Compensation :

Series capacitors are connected in series with the line, usually located at the mid-point, and are used to reduce the series reactance between the load and the supply point. This results in improved transient and steady-state stability, more economical loading, and minimum voltage dip on load buses. Series capacitors have the good characteristics that their reactive power production varies concurrently with the line loading. Studies have shown that the addition of series capacitors on EHV transmission lines can more than double the transient stability load limit of long lines at a fraction of the cost of a new transmission line. Figure 2 shows the shunt and series capacitor compensation.

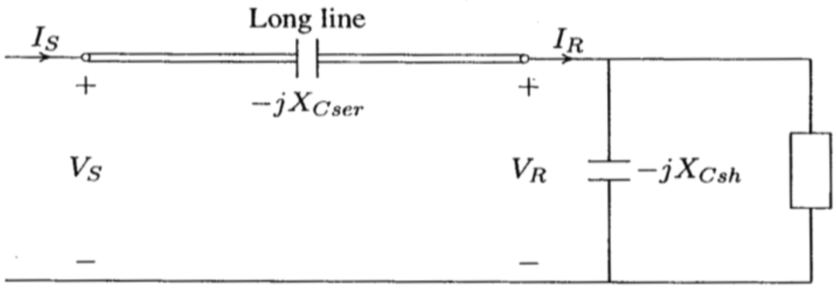


Figure (2): Shunt and Series Capacitor Compensation [7]

With the series capacitor switched on as shown in figure 2

$$P_{3\phi} = \frac{|V_{S(L-L)}||V_{R(L-L)}|}{X' - X_{Cser}} \sin\delta \qquad \text{..................(2)}$$

Where

$P_{3\phi}$ is the three – phase power transferred from sending end to receiving end.

$V_{S(L\text{-}L)}$ is the sending end line to line voltage

$V_{R(L\text{-}L)}$ is the receiving end line to line voltage

δ is the torque angle

X' is the transmission line reactance

X_{Cser} is the series capacitor reactance

The ratio X_{Cser} / X' expressed as a percentage is usually referred to as the percentage compensation. The percentage compensation is in the range of 25 to 70 percent.

One major drawback with series capacitor compensation is that special protective devices are required to protect the capacitors and bypass the high current produced when a short circuit occurs. Also, inclusion of series capacitors establishes a resonant circuit that can oscillate at a frequency below the normal synchronous frequency when stimulated by a disturbance. This subsynchronous resonance (SSR) frequency if subtracted from the synchronous frequency and the result approaches the frequency of one of the turbine-generator natural torsional modes, considerable damage to the turbine-generator may result. If L' is the lumped line inductance corrected for the effect of distribution and C_{ser} is the capacitance of the series capacitor, the subsynchronous resonant frequency is

$$f_r = f_s\sqrt{\frac{1}{L'C_{ser}}} \qquad \text{................(3)}$$

Where f_s is the synchronous frequency.

3. Power System Modeling :

Figure 3 shows the model of the power system that is used in Matlab/Simulink simulation which is a three – phase, 60 Hz, 735 kv power system transmitting power from a power plant consisting of six 350 MVA generators to an equivalent network through a 600 km transmission line. The transmission line is split in two 300 km lines connected between buses B1, B2, and B3. In order to increase the transmission capacity, each line is series compensated by capacitors representing a percentage value of the line reactance. Both lines are also shunt compensated by a 330 Mvar shunt reactance. The shunt and series compensation equipment are located at the B2 substation where a 300 MVA , 735/230 kv transformer with a 25 kv tertiary winding feeds a 230 kv, 100 MW load. The series compensation subsystems are identical for the two lines. The generators are simulated with a simplified synchronous machine block. Universal transformer blocks (two-windings and three-windings) are used to model the two transformers. Saturation is implemented on the transformer connected at bus B2. Voltages and currents are measured in B2 blocks. The simulated system in Matlab/Simulink is shown in appendix A.

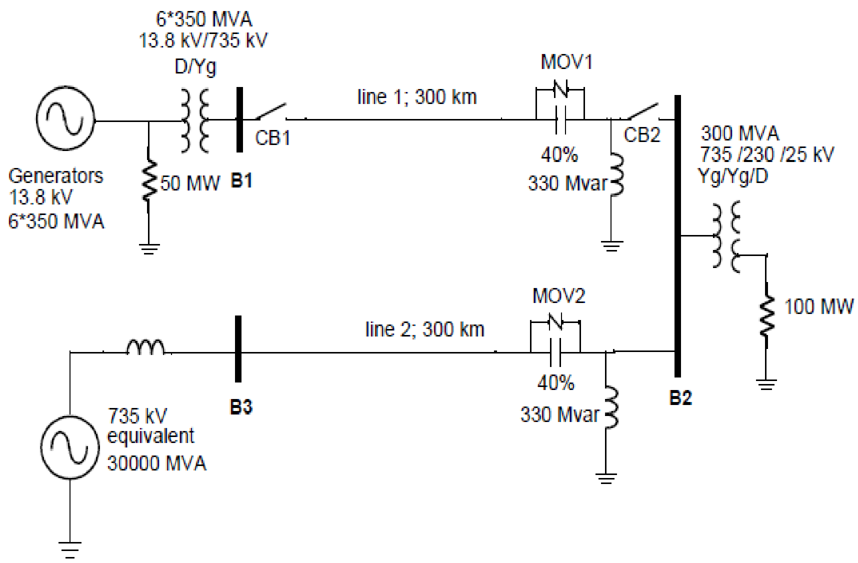


Figure (3): The Model of the Simulated Power System

4. Simulation Results and Discussion :

4.1. Calculation of Series Capacitance Required :

From transmission line data

Inductance per unit length = 0.9337 e-3 H/km

Line length (ℓ) = 300 km

Transmission line reactance is

$X_L = 2*\Pi*f*L*\ell$ Ω

$X_L = 2*\Pi*60*0.9337e\text{-}3*300$ Ω

$X_L = 105.6$ Ω

The percentage of the series compensation capacitive reactance required is

$X_C = 105.6 *$ percentage of compensation Ω

The required capacitor value is

$C = \frac{1}{2*\Pi*f*Xc}$ μf

Table 1 below gives the capacitor values for different percentage compensation

Table (1): Capacitor Values For Different Compensation Percentage

% compensation	25	30	35	40	45	50	55	60	65	70
C (μf)	100.3	83.6	71.6	62.7	55.7	50.1	45.6	41.8	38.6	35.8

4.2. Setting the Initial Load Flow and Obtaining Steady State :

Before performing transient simulation, the model must be initialized for the desired load flow. A load flow and synchronous machine initialization is performed for every series compensation percentage value used in this simulation in the range 25 to 70 percent. In this power system model there is only one synchronous machine and its bus type should be PV Generator and the desired terminal voltage should already be set to the nominal voltage (E) of 13.8 kv (1 pu). Once the load flow is solved, the required mechanical power (P_m) to drive the machine is calculated, this value and the 1 pu of E are entered in constant blocks already connected to the P_m and E inputs of the machine block. The load flow simulation results of P_m values for different values of series compensation percentage are given in table 2.

Table (2): P_m and E Values For Different Compensation Percentage

% compensation	25	30	35	40	45	50	55	60	65	70
E (pu)	1.026	1.017	1.008	1.007	1.039	1.037	1.035	1.035	1.0355	1.035
P_m (pu)	0.7441	0.7363	0.7212	0.7218	0.7475	0.7381	0.7402	0.7367	0.7334	0.7302

4.3. Frequency Analysis :

Figure 4 shows the impedance (magnitude and phase) as a function of frequency for 25% series compensation of the reactance of the transmission line, it can be seen that there are three main modes: 7 Hz, 147 Hz, and 350 Hz. The 7 Hz mode is mainly due to a parallel resonance of the series capacitor with the shunt inductors. The 147 Hz and 350 Hz modes are due to the 600 km transmission line distributed parameters. Table 3 shows the resonance modes for the series compensation in the range 25 to 70 percent.

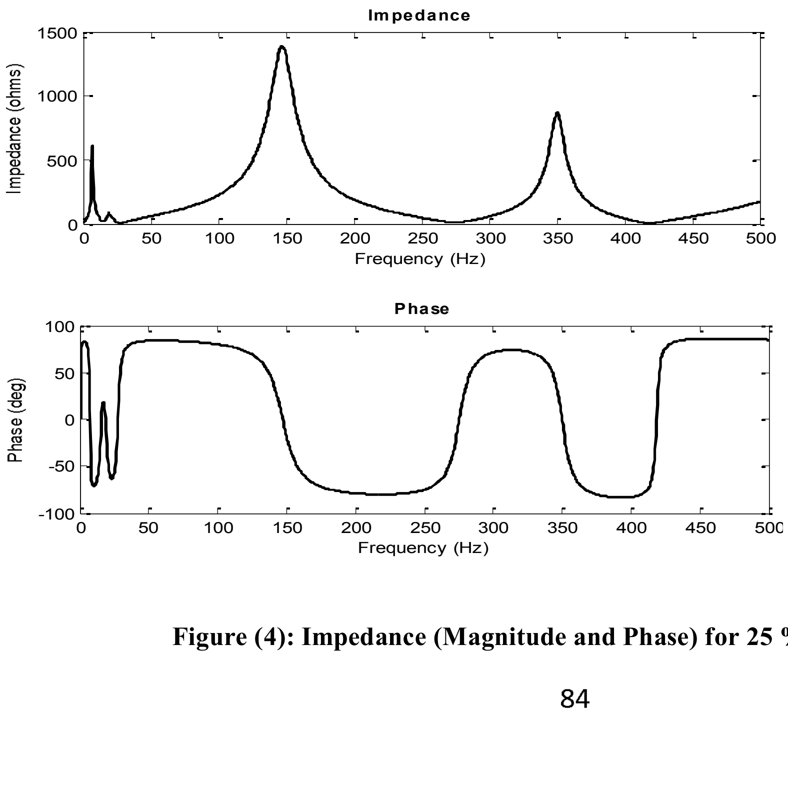


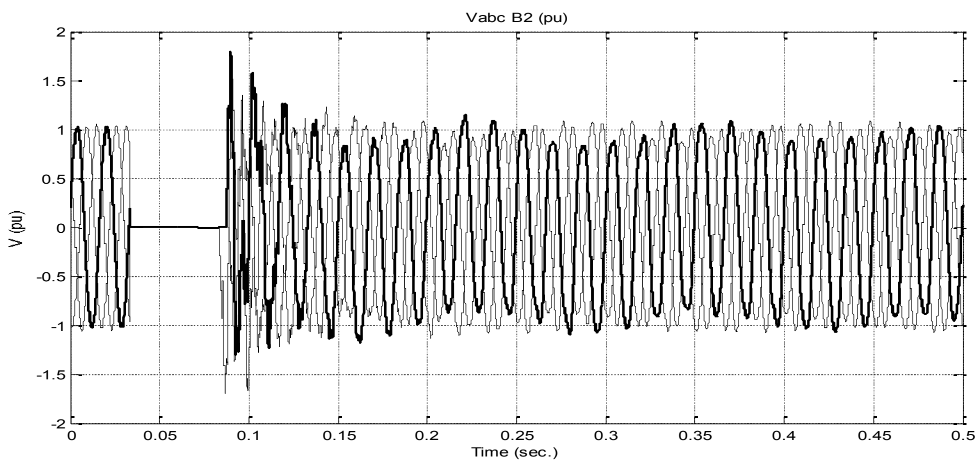
Figure (4): Impedance (Magnitude and Phase) for 25 % Compensation

Table (3): Resonance modes For Different Compensation Percentage

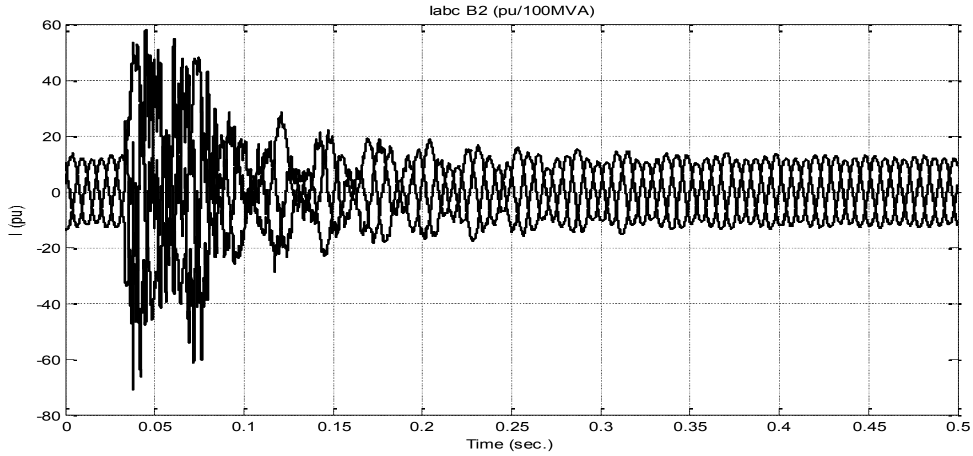
% compensation	25	30	35	40	45	50	55	60	65	70
Mode 1 (Hz) Subsynchronous Resonance	7	7.5	8.5	9	9.5	10	10.5	11	11.5	12
Mode 2 (Hz)	147	147.5	147.5	148	148	148.5	148.5	149	149	149.5
Mode 3 (Hz)	350	350.5	350.5	351	351.5	352	352	352.5	353	353

4.4 Transient Simulation for a fault at Bus B2

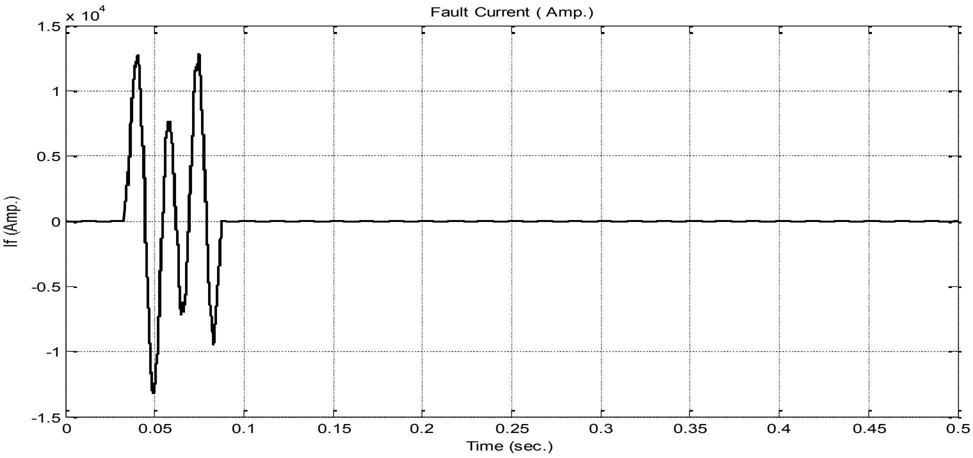
A three-cycle, three-phase to ground fault applied at t=2 cycle at bus B2, the two circuit breakers are not switching to clear the fault but they are stay at their initial state (closed). Figure 5 shows the simulation results of this transient contingency. Figure 5a shows the 3-phase to ground voltages in pu at B2, figure 5b shows the line current passing B2 in pu. Figure 4c shows the fault current in ampere. The 7 Hz subsynchronous mode excited at fault clearing is seen on the phase (a) voltage at bus B2 (figure 5d), this 7 Hz voltage component appearing at bus B2 drives the transformer which is connected to this bus into saturation, as shown on the transformer magnetizing current (figure 5e). The flux in phase (a) of the transformer is shown in figure 5f. T fault application the voltage at transformer terminals drops to zero and the flux stays constant during the fault. At fault clearing, when the voltage recovers, the transformer is driven into saturation as a result of the flux offset created by the 60 Hz and 7 Hz voltage components. The pulses of the transformer magnetizing current appear when the flux exceeds its saturation level. This current contains a 60 Hz reactive component modulated at 7 Hz.



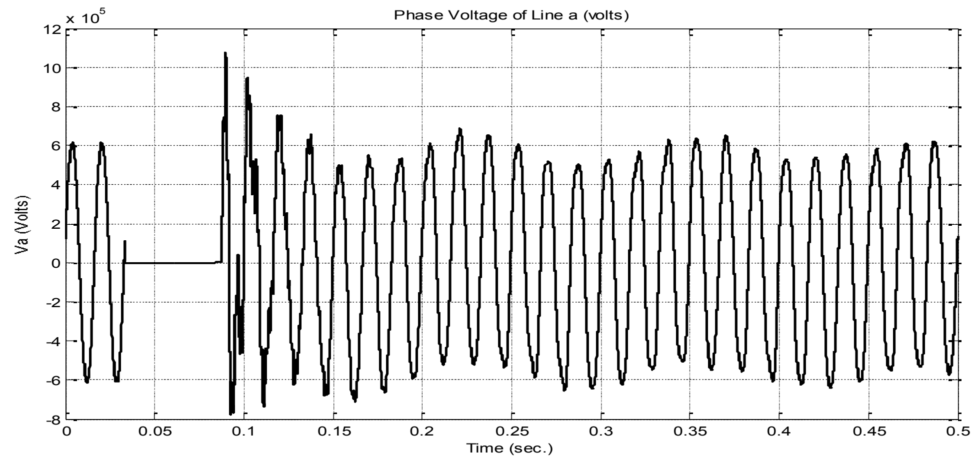
(a)


Iabc B2 (pu/100MVA)
I (pu)
Time (sec.)

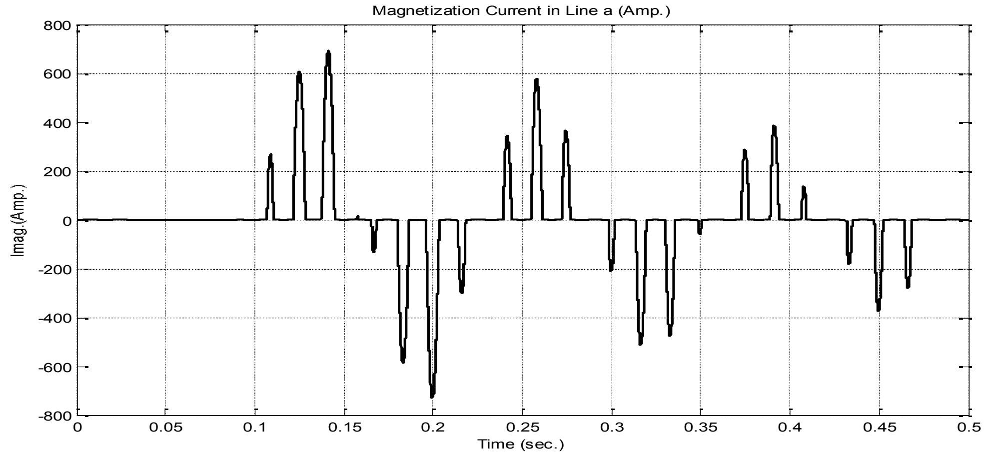
(b)


Fault Current (Amp.)
x 10^4
If (Amp.)
Time (sec.)

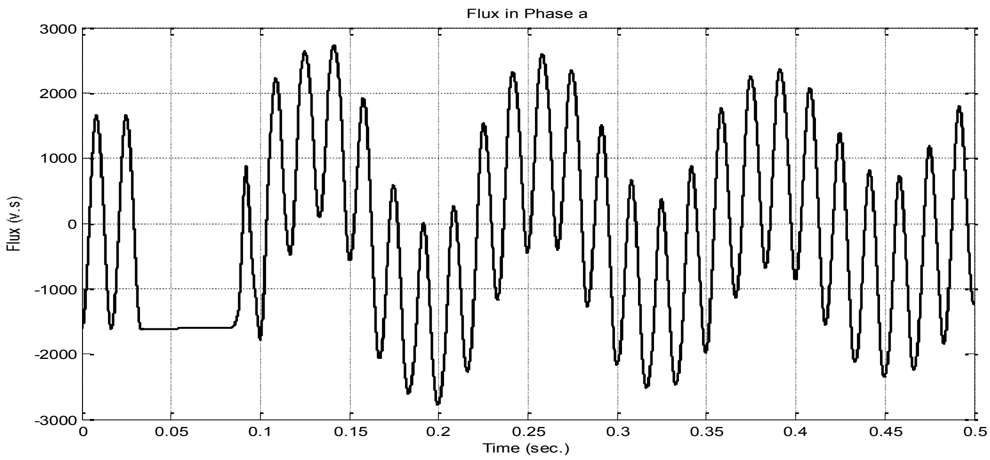
(c)


Phase Voltage of Line a (volts)
x 10^5
Va (Volts)
Time (sec.)

(d)



(e)



(f)

Figure (5): (a) 3-phase voltages, (b) 3-line currents, (c) fault current, (d) Phase voltage of line (a), (e) magnetizing current in line (a), (f) flux in phase (a).

5. Conclusion :

1. One particular characteristic of series-compensated systems is the existence of subsynchronous modes (poles and zeros of the system impedance below the fundamental frequency). Dangerous resonances can occur if the mechanical torsion modes of turbine/generator shafts are in the vicinity of the zeros of the system impedance.
2. High subsynchronous voltage due to impedance poles at subsynchronous frequencies will drive transformers into saturation.

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Appendix A

Mat-lab/Simulink version 7.6 (R 2008a)

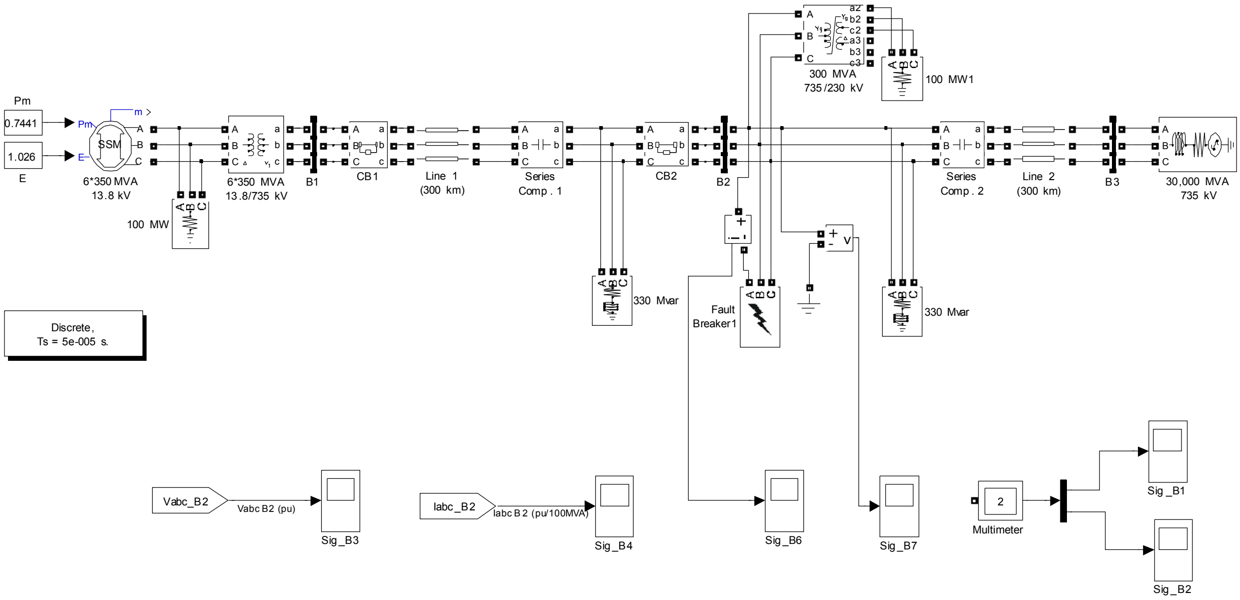

Figure A Matlab /Simulink simulation of the power system