Appendix A
Data of the System Under Study

The data of the system under study are as follows:
Base M.V.A =892.4
Base k.v =500

A.1 Inertia and stiffness Constants:

M_H=0.185795	M_I=0.311178
M_A=1.717340	M_B=1.798430
M_G=1.736990	M_X=0.068433

Spring constant are in pu torque/rad

K_{HI}=19.303	K_{IA}=34.929	K_{AB}=52.038
K_{BG}=70.858	K_{GX}=2.822	

$D_H = D_I = D_A = D_B = D_G = D_X = 0.0$

A.2 Turbine and Governor:

F_H=0.3	F_I=0.26	F_A=F_B=0.22
T_{CH}=0.3 s	T_{RH}=7 s	T_{CO}=0.2 s
K_G=25	T_{SR}=0.2 s	T_{SM}=0.3 s

A.3 Transformer and Transmission Line:

The next values are in p.u:

R_T=0.01	X_T=0.14
R_E=0.02	X_E=0.5
	X_{Tr} =0.06
	X_L=0.06+0.5=0.56

A.4 The Synchronous Generator:

The next values are in p.u:

X_{ad}=1.66	X_d=1.79	X_D=1.666
X_{aq}=1.580	X_q=1.710	X_Q=1.695
X_F=1.7	X_G=1.825	
R_a=0.0015	R_F=0.001	R_D=0.0037
R_G=0.0182	R_Q=0.0053	

A.5 Exciter and Voltage Regulator:

K_A=25 T_E=0.002 s T_A=0.01 s

A.6 The Initial Operating Conditions:

P_o=1 p.u V_t=1.05 p.u V_o=1p.u

Power factor=0.9

A.7 STATCOM

X_S=0.15 p.u

CHAPTER (1)

INTRODUCTION

1.1 GENERAL

The electric utility companies are faced with growing demand of electrical energy, and simultaneously ensuring reliability of an electrical supply. The modern electrical power system grid has become a highly integrated transmission network comprising many synchronous generators, ac lines, dc lines, passive and active loads, and numerous controllers.

The increased transmission demand is met by increasing the existing transmission capacity. Series capacitor compensation is employed in electric power systems to raise the power transmission limit of long EHV lines. This, however, may lead to the phenomenon of subsynchronous resonance (SSR). SSR occurs when a natural frequency of a series compensated transmission system aligns with the complement of one of the torsional modes of turbine-generator. This happens at sub-synchronous frequencies. Under such circumstances, the turbine-generator oscillates at a frequency corresponding to the torsional mode frequency, and unless corrective action is taken, the torsional oscillations can continue for a long time and may result in the failure of the turbine-generator shaft. There are several countermeasures proposed in the literature to avoid such a condition [1-14].

Protection engineers noted that, on the two Mohave SSR incidents, negative-sequence relays protecting the generating units issued alarms, indicating the presence of negative-sequence currents [11]. This indicated that the negative-sequence relay might be sensitive to subsynchronous frequencies .The negative-sequence relay produced a signal at 30hertz even without the presence of any negative-sequence currents. This concept became the basis for the design of a new SSR relay that was later designated the armature current SSR relay (TEX relay) by the addition of suitable band-pas blocking filters [11, 15].

1.2 DIFFERENT TYPES OF SUBSYNCHRONOUS RESONANCE

SSR phenomena have been in the center of interest since many years, and the subject has always been discussed in a multitude of publications (e.g. [1-4]) . Up to now only systems consisting of one or more turbine generators feeding a long compensated transmission line where severe damages occurred have been investigated. But in the last few years it became obvious that also other circumstances or conditions can lead to an electromechanical resonance without capacitors being used to compensate transmission lines. These phenomena, where also damages can occur, are also found quite often. So it is reasonable to investigate them more closely [16, 17].

1.2.1 The Conventional SSR Phenomena

The conventional SSR phenomena caused by compensated transmission lines can be manifested in three forms:
Induction generator effect (IGE), torsional interaction (TI) and torque amplification (TA). These phenomena may occur isolated or simultaneously, and when they occur they can cause damaging oscillations. Hazardous levels might be reached within 0.1 seconds [16].

1.2.2 SSR Caused By Feed Water Pumps Fed By Thyristor Cascades

A quite different mode of excitation of subsynchronous natural frequencies in turbine generator shafts by subsynchronous components in the electrical torque was observed in a 775 MW turbine generator in Germany. The SSR was detected by a torsional stress analyzer (TSA). The boiler feed-water pumps of this power plant were driven by power-converter-controlled asynchronous motors as illustrated in Fig. 1.1

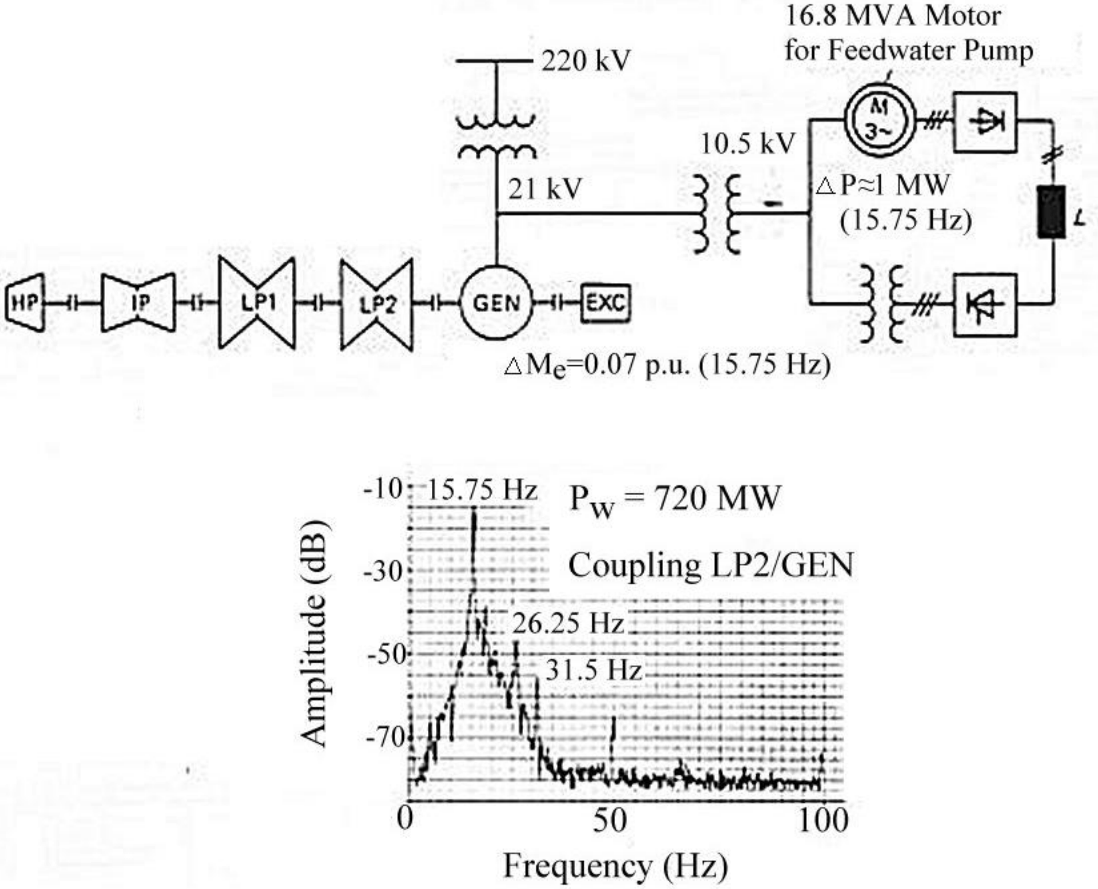

Fig. 1.1 Subsynchronous torsional resonance of a 775 MW turbine generator due to feedback from a thyristor cascade

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. So this pulsation in the electrical torque was amplified by the oscillating generator rotor [16].

1.2.3 Electro-Mechanical Resonance During Running Up Of A Squirrel Cage Induction Machine

In [16] an example for electromechanical resonance in case of a motor and main engine coupled via hitch and gear is given. A model of the investigated system is shown in Fig. 1.2.

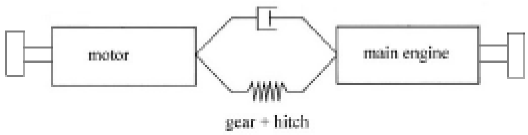

Fig. 1.2 Model for drive system

The numerical calculation of different types of drives brought an important insight: also in systems with induction machines an electromechanical resonance can occur, especially during running up. Consequently 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. Also the inner mechanical damping has to be considered.

1.2.4 SSR Caused By Slip Ring Machines With Faulty Rotor Windings

A totally new SSR caused phenomena was by slip ring machines with faulty rotor windings connected to a closely meshed private power system with synchronous generators. In a plant for natural gas liquefaction, some electrical machines were damaged at the same time. On one hand, the slip ring connection of a 7 MW 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 following hypothesis was assumed: 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.

1.3 SERIES COMPENSATION

For many years, series compensation has been used in power systems to compensate for the longitudinal voltage drop, increase stability margins, and to control load sharing between parallel transmission paths. The main purpose of a series capacitor is to generate reactive power compensation. The lines reactive power consumption is given by jX_LI^2. As the line reactance is constant, by adding variable series capacitor the amount of compensation is controlled. The % compensation of the line is defined as

$$\%\ \text{compensation} = \frac{X_C}{X_L} \times 100 \qquad (1.1)$$

Where X_L is the line reactance and Xc is the series capacitor reactance. New capacitor technology ("all-film") has reduced losses and weight of the capacitor banks and decreased the space required for their installation [7].

Subsynchronous resonance (SSR) is a dynamic phenomenon of interest in power systems that have certain special characteristics. The formal definition of SSR is provided by the IEEE **:**
"Subsynchronous 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." [3,7-9,11,18-20]

This energy exchange can take place at *natural* modes of oscillation that are due to inherent system characteristics, as well as at *forced* modes of oscillation that are driven by a particular device or control system. The most common example of the natural mode of subsynchronous oscillation is due to networks that include series capacitor compensated transmission lines. A capacitor in series with the inductance forms a series resonant circuit with a natural frequency given by

$$f_e = \frac{1}{2\pi\sqrt{LC}} = f_o \sqrt{\frac{X_C}{X_L}} \qquad (1.2)$$

Where Xc is the reactance of the capacitor, X_L is the total reactance of the line, both defined at the power frequency f_o,. X_L comprises subtransient reactance of the generator, reactance of the transformer, line and load. These frequencies appear to the generator rotor as modulations of power frequency, giving both subsynchronous and supersynchronous rotor frequencies. The latter are usually suppressed by the damper winding. It is the subsynchronous frequency that may interact with one of the torsional modes of the turbine-generator shaft, thereby setting up the conditions for an exchange of energy at a subsynchronous frequency, with possible torsional fatigue damage to the turbine-generator shaft.

The torsional modes (frequencies) of shaft oscillation are usually known (supplied by the manufacturer). The network frequencies depend on many factors, such as the amount of series capacitance in service and the network switching arrangements at a particular time. A series capacitor compensated transmission network can cause sustained or negatively damped subsynchronous oscillations by two distinctive mechanisms, viz., self excitation due to induction generator effect and interaction with torsional oscillations[3,5,7,8,10,11,21].

1.4 TYPES OF SSR INTERACTIONS

There are many ways in which the system and the generator may interact with subsynchronous effects. A few of these interactions are basic in concept and have been given the following special names:

1. Induction Generator Effect

2. Torsional Interaction Effect
3. Transient Torque Effect

1.4.1 Induction Generator Effect

Induction generator effect is caused by self excitation of the electrical system. The resistance of the rotor to subsynchronous current, viewed from the armature terminals, is a negative resistance. The network also presents a resistance to these same currents that is positive. However, if the negative resistance of the generator is greater in magnitude than the positive resistance of the network at the system natural frequencies, there will be sustained subsynchronous currents. This is the condition known as the "induction generator effect."

If saliency is neglected, the per phase equivalent circuit of synchronous machine at subsynchronous frequencies (f_e) consists of series combination of R_{eff} and X_{eff}

$$R_{eff} = R_a + \frac{R_r}{s}$$

$$X_{eff} = X_l + X_r, \qquad (1.3)$$

$$s = \frac{f_e - f_o}{f_e}$$

Where Ra is the stator resistance, R_r, is the rotor resistance, S is the slip and f_o, is the synchronous frequency. Suppose that subsynchronous currents have been transiently excited by a disturbance in the external system. The generator stator current components of frequency f_e, will set up a magnetic flux at $2\pi f_e$ elec rad/s angular velocity. The rotor is rotating at $2\pi f_o$ elec rad/s, faster than the subsynchronous field. Since $f_e < f_o$ the slip is negative, and the rotor behaves much like that of an induction motor running above synchronous speed. Depending on f_e, the effective resistance, R_{eff}, can be negative. At high degrees of series compensation, this apparent negative resistance may exceed the network resistance, effectively resulting in an RLC circuit with negative resistance. Such a condition will result in self excitation causing electrical oscillations of intolerable levels. The tendency toward this electrical subsynchronous instability is decreased by increasing the network resistance, and by decreasing the resistance of generator rotor circuits (for example by providing a good pole face damper winding) [10,11,22,23].

1.4.2 Torsional Interaction

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

In other words if the complement of the natural frequency (f_o-f_e) of the network is close to one of the torsional frequencies of the turbine-generator shaft system, torsional oscillations can be excited. Under such conditions, a small voltage induced by rotor oscillations can result in large subsynchronous currents; this current will produce an oscillatory component of rotor torque. Moreover, the induced subsynchronous frequency voltage is phased to sustain the subsynchronous torque. If this torque equals or exceeds the inherent mechanical damping of the rotating system, the coupled electromechanical system will experience growing oscillations.

The machines which are most susceptible to SSR are large multiple-stage steam turbines, which typically have four or five torsional modes in subsynchronous frequency range. The consequences of a SSR condition can be dangerous in the short term, if the oscillations are unstable and build up sufficiently, the shaft can break. But even if oscillations are relatively well damped, disturbances (like switching, fault clearing, etc.) can diminish the shaft life due to mechanical fatigue [22,23].

1.4.3 Transient Torques

Transient torqueses are those that result 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. In a transmission system without series capacitors, these transients are always dc transients, which decay to zero with a time constant that depends on the ratio of inductance to resistance. For networks that contain series capacitors, the transient currents will be of a form similar to $i_t = K[A\sin(\omega_1 t + \psi_1) + Be^{-\omega_2 t}\sin(\omega_2 t + \psi_2)]$ and will contain one or more oscillatory frequencies that depend on the network capacitance as well as the inductance and resistance. In a simple radial *R-L-C* system, there will be only one such natural frequency but in a network with many series capacitors there will be many such subsynchronous frequencies. If any of these subsynchronous network frequencies coincide with one of the natural modes of a turbine-generator shaft, there can be peak torques that are quite large since these torques are directly proportional to the magnitude of the oscillating current. Currents due to short circuits, therefore, can produce very large shaft torques both when the fault is applied and also when it is cleared. In a real power system there may be many different subsynchronous frequencies involved and the analysis is quite complex [7].

Of the three different types of interactions described above, the first two may be considered as small disturbance conditions, at least initially. The third type is definitely not a small disturbance and nonlinearities of the system also enter into the analysis. From the viewpoint of system analysis, it is important to note that the induction generator and torsional interaction effects may be analyzed using linear models, suggesting that eigenvalue analysis is appropriate for the study of these problems.

1.5 SSR COUNTERMEASURES

There are two conditions that create little or no concern regarding SSR for extensive application of series compensation.

1. The first condition is where the generators connected to the system are driven by hydraulic turbines. In the hydro-turbine generator system, the ratio of generator mass is significantly higher than the corresponding ratio of steam-turbine generator system. The large mass of the hydro generator increases the effective modal damping and modal inertia making it essentially impossible to excite the natural torsional frequencies of the turbine generator system.

2. When generators are connected to the non-compensated lines.

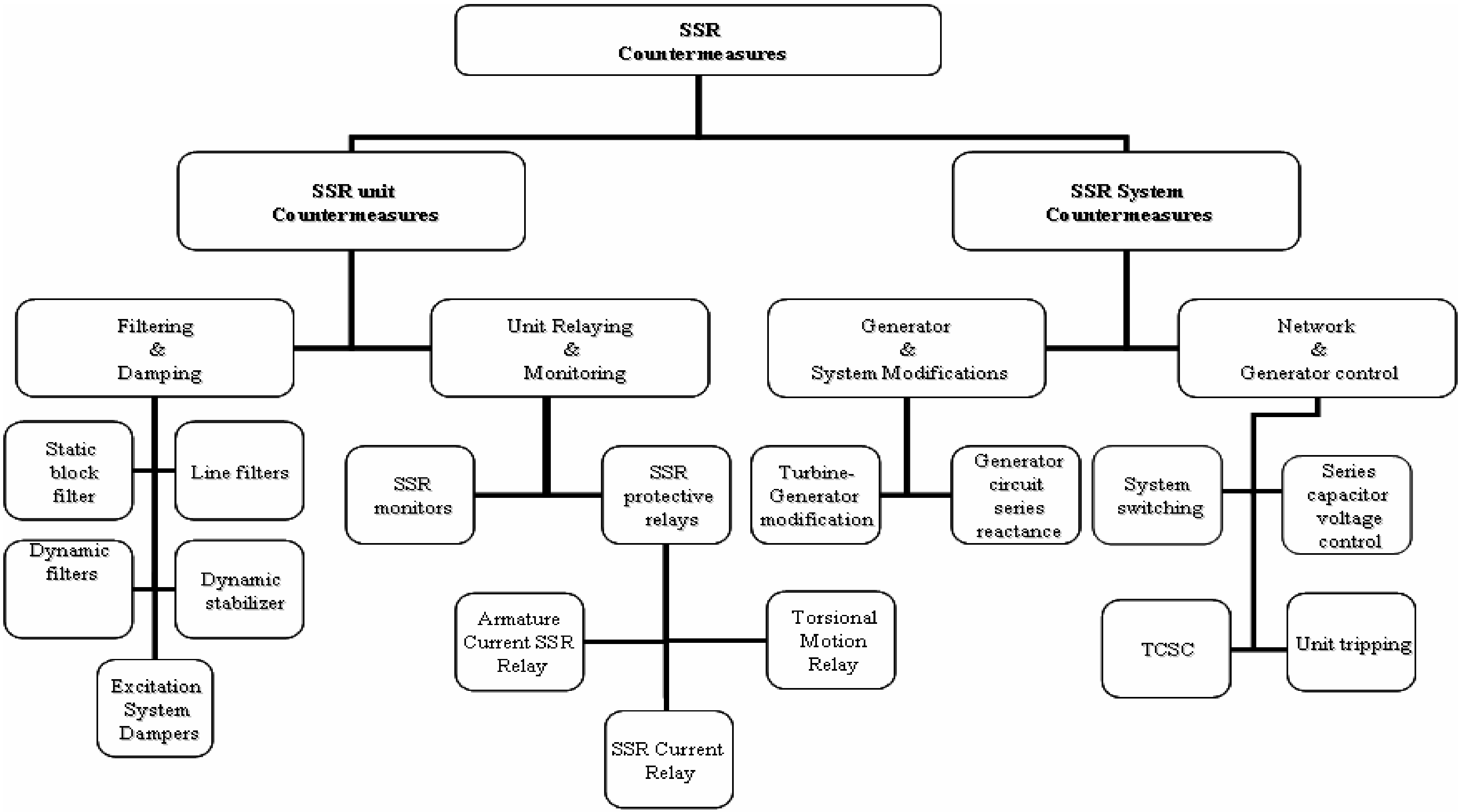

Fig 1.3 Types of SSR Countermeasures

A wide variety of methods have been proposed in the literature for damping SSR oscillations, several countermeasures have been applied and more have been suggested in the literature. Regarding the elimination of the induction generator effect, they recommend that the generator be equipped with poleface amortisseurs. As for the mitigation of the torsional interaction effect, they suggest the installation of filters in series with the generator to increase the circuit resistance for each torsional mode. Finally, to reduce the transient torque on the turbine-generator shafts to the level that shaft fracture may not occur for any single transient incident, they suggest the adoption of a capacitor dual gap flashing scheme. Because of the high amplitudes of oscillations and the fast torque build up, transient torque problems require more extreme and costly countermeasures than those needed to mitigate the self-excitation cases. Fig.1.3 summarize almost all types of SSR protection

1.6 UNIT RELAYING

A protective relay is a good method against SSR that can detect the problem and trip the unit before shaft fatigue has accumulated to a significant level. Most of the other countermeasures are designed to make sure that there is good damping of subsynchronous oscillations and to shield the turbine-generator unit from experiencing these oscillations, insofar as possible. Despite all precaution, there may be occasion where a generation unit will be exposed to subsynchronous oscillations. There is always the possibility that conditions are not ideal. The countermeasures in service may not be working correctly, or may be disabled. Should such an unforeseen event occur, it is not an acceptable risk that a generating unit should be caused to sustain long or growing subsynchronous oscillation. Therefore, SSR relays are usually installed to make sure that the unit life is preserved, even under conditions that are extremely rare. In some cases, where the risk of SSR damage is limited or the dangerous conditions are rare, the relay may be the only SSR countermeasure required.

There are different types of SSR relays that have been provided to meet the requirements of detection of potential damaging oscillations and removal of the unit. Two of the relays are based primarily on the monitoring of the frequency content of the generator currents. The third relay models the mechanical behavior of the turbine-generator shaft; each of these relays will be briefly described.

1.6.1 Armature Current SSR Relay

Negative-sequence relays protecting the generating units issue alarms, indicating the presence of negative-sequence currents. This indicates that the negative-sequence relay design might be sensitive to subsynchronous frequencies. Laboratory tests of a similar relay confirmed this characteristic. In fact, the negative-sequence relay produced a signal at 30 hertz, even without the presence of any negative sequence current. This concept became the basis for the design of a new SSR relay that was later designated the TEX relay, by the addition of suitable band-pass and blocking filters. The TEX relay has the following design features [11,24]:

-Detects positive-sequence currents in the 20-40 hertz rang,

-Provides two subsynchronous current level detectors that are separately adjustable,

-Is relatively insensitive to low system frequency operation,

-Is relatively insensitive to generator negative-sequence current, and

-Has sufficient time delay to override SSR currents associated with normal system operation, such as system faults and series capacitor switching.