IEEE TRANSACTIONS ON MAGNETICS, VOL. 27, NO. 2, MARCH 1991

FUNDAMENTAL ANALYSIS OF DYNAMIC STABILITY IN SUPERCONDUCTIVE POWER SYSTEMS

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Abstract

Applications of superconductivity to power systems have many possible advantages in economy, reliability and stability. On the other side, superconductive power systems have risks of including insufficient damping due to the effect of inductance-capacitance (LC) resonance. This may cause subsynchronous resonance oscillations (SSR) represented by self-excited oscillation and torsional oscillation of rotor-turbine shafts. The main subject of this paper is to analyze numerically SSR and electro-mechanical power swing in a model power system with superconductive power apparatus. A stabilizing control scheme which uses the stored energy in the field winding circuit of superconductive generator, is applied to some instabilities and its effectiveness is confirmed in a digital simulation study.

Introduction

The phenomenon of superconductivity has been producing many technical innovations in various industrial fields since it was discovered in 1911. The discovery of high temperature superconductive materials in recent years has accelerated the progress in the applications of superconductivity. Under these circumstances the applications of superconductivity to power systems are expected as a means of constructing extremely economical and stable power systems, and an idea to manufacture most of the elements of power generation and transmission from superconductive materials, becomes realistic. This paper analyzes fundamental characteristics of the dynamics of a superconductive power system.

Some advantages of introducing superconductivity into power systems are: 1) reduction in losses, 2) improvement in system stability, 3) reduction in size and weight of power devices. However, a possible disadvantage may be the fact that superconductive power systems are to be made up with circuits with no resistance at all. This means that the power systems may have insufficient damping effect with respect to LC resonance. This may cause what is called SSR oscillations which are represented by self-excited oscillation and torsional oscillation of rotor-turbine shafts[1,2,3].

In this paper the features of instability in a long distance bulk power transmission model system with superconductive power transmission lines or with superconductive synchronous generators are analyzed numerically. First, it is shown that self-excited oscillation is easily induced in superconductive AC power transmission systems. Second, torsional oscillation and electro-mechanical power swing in a model power system with superconductive turbine generator power plant are analyzed for various system conditions, and it is confirmed in a digital simulation study that an adequate energy control of field winding of superconductive generator[4] can stabilize the power system.

Configuration of Model Power System and Stability Analysis

Figure 1 shows the configuration of a model power system used for the analysis in this paper. It is a basic one machine-infinite bus system with a 5,600 MVA power plant containing five identical 1,120 MVA turbine generators connected to a large power system through 500 kV and about 400 km double circuit transmission lines. The behavior of generator, the mechanical characteristic of rotor-turbine shafts and the electrical characteristic of the transmission system are represented by the Park's model, a mass-spring model and a set of differential equations of LC resonance, respectively.

First, we have analyzed the stability of the power system with conventional parameters of normal conductivity. System constants are shown in Tab. 1.

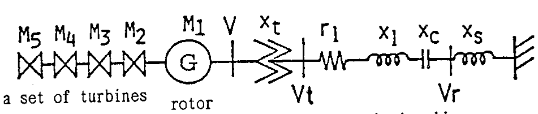

Figure 1. A model power system.

Table 1. Power system constants.

Transmission system (5,600 MVA, 500 kV base)					
	x_t=0.197	x_s=0.193	r_1=0.0463	x_1=1.40	
Generator (1,120 MVA machine base)					
armature:	x_d=1.6	x_q=1.6	r_a=0.00181		
damper:	x_{kd}=1.38	x_{kq}=1.37	r_{kd}=0.0062	r_{kq}=0.0124	
rotor:	x_f=1.44	r_f=0.0006	(T_{do}'=6.37 s)		
mutual:	x_{md}=1.35	x_{mq}=1.35			
inertia (in sec):					
	M_1=1.181	M_2=1.90	M_3=1.86	M_4=1.81	M_5=0.40

In this power system series capacitors are used for compensating the reactance of long distance transmission lines. Figure 2 shows the system eigenvalues associated with LC resonance for different series compensation rates to line reactance x_1. Slip between the commercial frequency 1.0 pu (60 Hz) and the frequency f_{LC} pu of LC resonance produces a higher mode with frequency of $1+f_{LC}$ pu and a lower mode with frequency of $1-f_{LC}$ pu. The stability problems in this case are: 1) Interaction between the lower mode and the mechanical oscillation modes of generator shaft produces unstable torsional oscillations. The rates of series capacitor compensation which causes the instability are 70 % and 92 %. 2) The lower mode of LC resonance becomes unstable by itself. It occurs when the rate of compensation is more than 108 %.

Another well-known instability is the electro-mechanical mode with about 1 Hz frequency whose principal motivation is given by the generator inertia. It tends to occur when the transmission power flow becomes heavy. Figure 3 shows the aspect of the instabilities for different amounts of transmission power.

It is commonly said that the instabilities of SSR are caused by the insufficient damping of LC resonance due to small resistance in an ultra high voltage bulk

Manuscript received September 24, 1990.

0018-9464/91/0300-2349$01.00

power transmission system. Therefore, in the case of the power system with superconductivity the situation must be more serious. In this paper these system stabilities are to be evaluated for the cases that superconductivity is introduced to

1) the AC power transmission system,
2) the synchronous turbine generator.

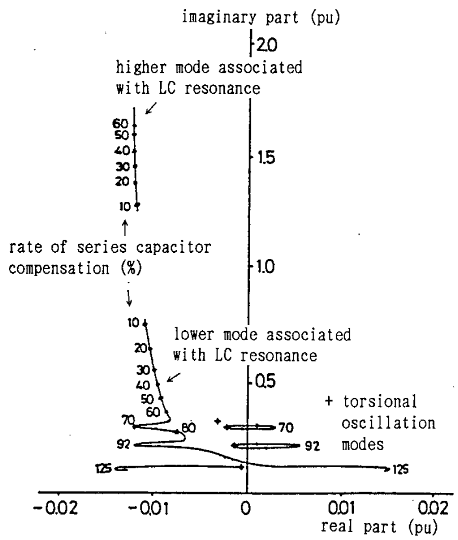

Figure 2. Result of calculating system eigenvalues associated with LC resonance for different series capacitor compensation rates.

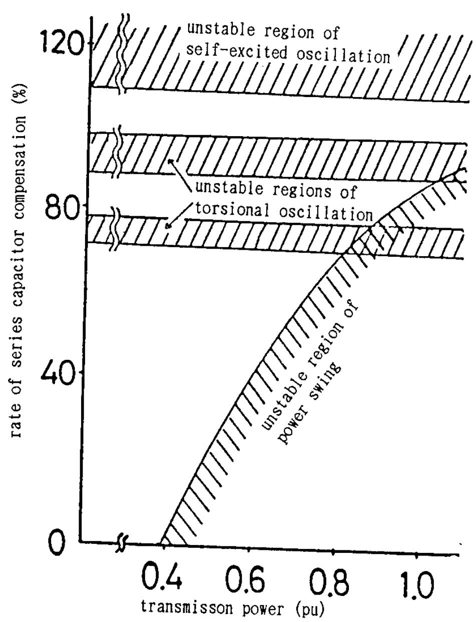

Figure 3. Result of calculating unstable regions for different amounts of transmission power.

Self-Excited Oscillation in Superconductive AC Power Transmission System

In a long distance bulk power transmission system, it is economical to replace conventional normal conductive transmission lines by superconductive ones from the point of view of loss reduction. Even in this case, series capacitor compensation may be an effective means to increase transmission capacity because reactance of the line still remains. In addition to this, electrostatic capacitance of the superconductive transmission line may be large because it is made not of overhead wire but of underground cable. Therefore, we should pay attention to the existence of LC resonance circuits in superconductive AC power transmission system.

Here, the self-excited oscillation is analyzed by using the model power system shown in Fig. 1 where the resistance of transmission line r_1 is set to be 0. Figure 4 shows the results of calculating eigenvalues associated with the LC resonance modes for different rates of series capacitor compensation. In the case of normal conductive power transmission, neither higher nor lower modes are unstable as long as the capacitor compensation rate is under 60 %. However, in the case of superconductive power transmission, the lower mode is always unstable regardless of the rate of capacitor compensation.

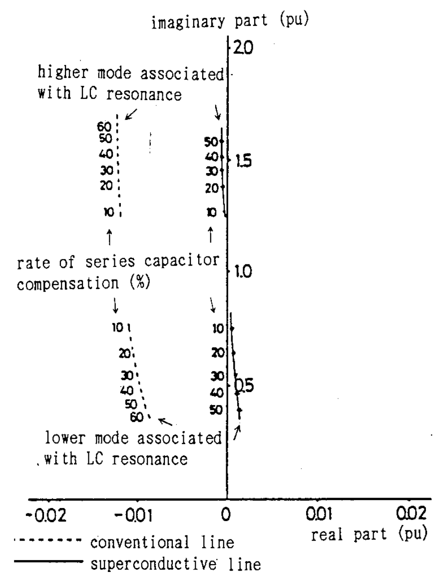

Figure 4. Result of calculating system eigenvalues associated with LC resonance in the model power system with superconductive power transmission line.

The corresponding simulation results are shown in Fig. 5 where the series compensation rate is 20 %. The assumed system disturbance is that the infinite bus voltage drops to 0.8 pu from the initial value of 1.0 pu for four cycles, which represents four cycle 3-phase short circuit at a distant place from the generator. Self-excited oscillation grows exponentially, and finally, the power system gets to a breakdown.

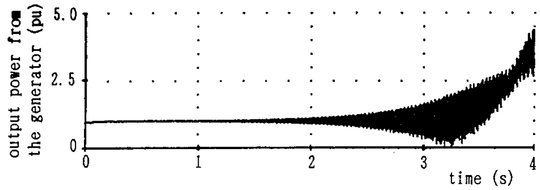

Figure 5. Simulated waveform in which self-excited oscillation is unstable.

Stability Analysis of the Power System with Superconductive Generator

Second example is the stability analysis in the power system with superconductive synchronous turbine generators. Unstable regions of the power system are calculated in the case that the generators in Fig. 1 are replaced by superconductive ones. Parameters of the generator is shown in Tab. 2. The results of calculation are shown in Fig. 6.

Table 2. Parameters of superconductive generator.

Generator (1,120 MVA machine base)					
armature:	$x_d=0.3$	$x_q=0.3$	$r_a=0.00016$		
damper:	$x_{kd}=0.17$	$x_{kq}=0.17$	$r_{kd}=0.0065$	$r_{kq}=0.00975$	
rotor:	$x_f=0.29$	$r_f=0.0000006$ ($T_{do}'=1300$ s)			
mutual:	$x_{md}=0.17$	$x_{mq}=0.17$			
inertia (in sec):					
$M_1=0.81$	$M_2=1.90$	$M_3=1.86$	$M_4=1.81$	$M_5=0.40$	

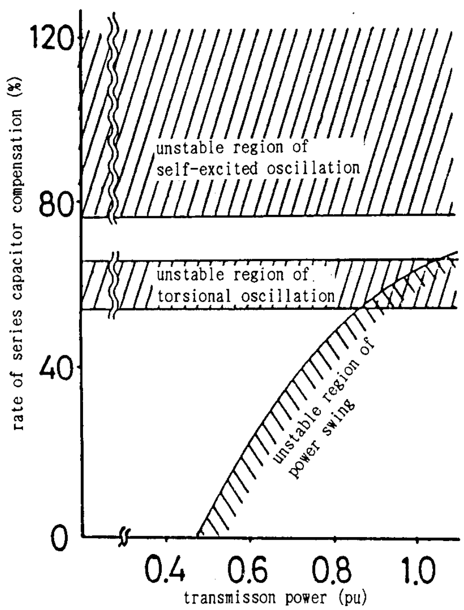

Figure 6. Results of calculating unstable regions in the power system with superconductive generator.

As for the power swing, stable region becomes larger when the superconductive generators are introduced. It is because the values of reactance of superconductive generator, especially synchronous reactance, are rather small. Since the inertia constant of the rotor of superconductive generator is smaller than that of conventional one, the frequency of the torsional oscillation mode becomes a little higher. As a result an unstable mode associated with the torsional oscillation appears at smaller rates of capacitor compensation.

It is also a distinctive feature of the power system with superconductive generator that the unstable region of self-excited oscillation is larger. This is mainly caused by the smaller armature resistance of the superconductive generator.

Power System Stabilization by the Energy Control of Superconductive Generator

The power system stabilizing control scheme by using the energy of field winding of superconductive generator has been proposed and its effectiveness for the electro-mechanical power swing has been also confirmed numerically[4]. Here, we apply a similar control scheme for the stabilization of the torsional oscillation as well as of the power swing.

A schematic image of the system configuration is shown in Fig.7. Superconductive circuit of the field winding is connected to the generator terminal through an AC/DC power converter. The converter has a function of controlling the active power output P so as to follow a specified value. Here, the following control scheme for the power system stabilization is applied.

$$\Delta P=\{1/(1+T_D s)\}\{1/(1+T_L s)\}(K_1\Delta V-K_2\Delta\omega_1)$$

where the first term is an assumed time-lag of power control, T_L is a time constant of the low pass filter, V is the generator terminal voltage and ω_1 is the phase angular velocity of the rotor. Δ denotes the deviation from the operating point of the variable. The AC/DC power converter operates the direct (d) and quadrature (q) axis components of the output AC current (I_{sd} and I_{sq}) and realizes the output power P. The reactive power output is controlled to be always zero. The relation between the power and the currents is represented by

$$P=I_{sd}V_d+I_{sq}V_q,$$
$$0=I_{sq}V_d-I_{sd}V_q$$

where V_d and V_q are the d- and q- components of the generator terminal voltage.

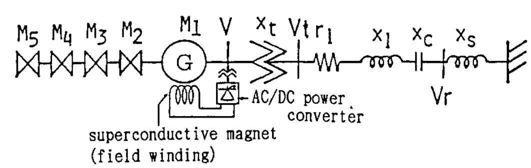

Figure 7. A configuration of the power system including superconductive generator with a power system stabilizing controller.

The results of digital simulation are shown in Fig. 8 where the transmission power is 0.5 pu and the rate of series compensation is 20 %. θ_1 is the rotor phase angle. The fault was assumed that the infinite bus voltage drops from 1.0 pu to 0.8 pu for four cycles. Parameters of the controller T_L, K_1 and K_2

were set to be 0.01 s, 0.5 pu and 10.0 pu, respectively. T_D was set to be 0.01 s. Without control, both power swing mode and torsional oscillation mode are hardly damped. When the proposed control is applied both of the modes are simultaneously stabilized effectively, although another higher torsional mode shift a bit to unstable side.

Conclusion

In this paper fundamental studies on dynamics of the long distance bulk power transmission model system with superconductive power apparatus are described. The obtained results are summarized as follows.

(1) In the superconductive AC transmission system with series capacitor compensation, unstable self-excited oscillation is easily induced.

(2) In the power system with superconductive generator the instability region of electro-mechanical power swing becomes smaller due to the reduction of generator reactance. However, the unstable regions of torsional oscillation and self-excited oscillation becomes wider.

(3) The power system stabilization by means of the energy control of field winding in superconductive generator has been applied to the model system. It has been numerically confirmed that the control scheme is effective not only for the power swing but also for the torsional oscillation.

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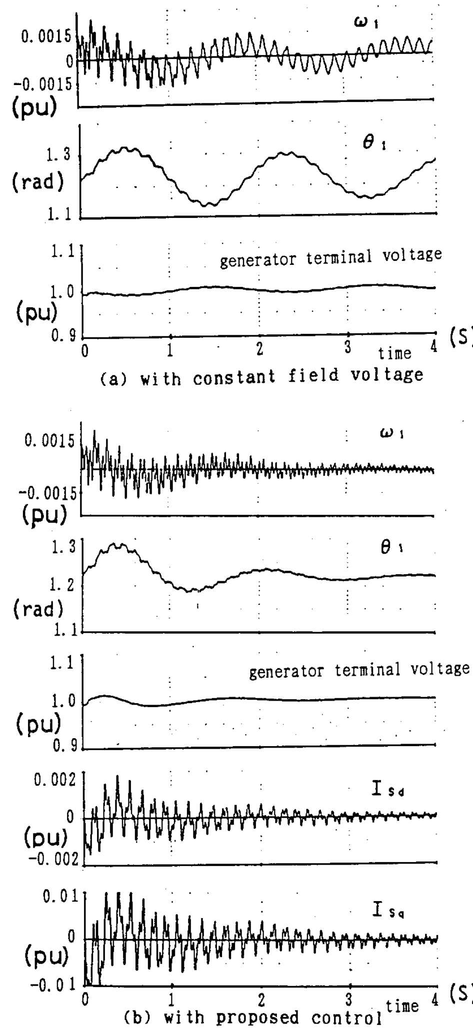

Figure 8. Simulated waveforms of the cases without control and with the proposed stabilizing system.