Effect of Compensation Factor on the Subsynchronous Resonance in Single Machine Infinite Bus System

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Abstract - Subsynchronous resonance phenomenon is studied in single machine infinite bus system. The system is composed of synchronous generators connected through transmissions line, compensated by a series capacitor to an infinite bus bar. The control parameter is the compensation factor which is the ratio between the reactance of the series capacitor and the inductance of the transmission line \( \mu = \frac{X_c}{X_L} \). The stability of system is studied by evaluating the Eigenvalues of the Jacobian matrix of the system. The effect of varying the compensating factor and the effects of AVR and PSS are also considered in this study.

Key Words - subsynchronous resonance, power system stabilizer (PSS), automatic voltage regulator (AVR), Eigenvalues.

I. INTRODUCTION

A compensation series capacitor is widely used in power systems to improve their stability and increase the power capability transfer over their transmission lines. Although series compensation capacitor technique has these advantages, it causes undesirable interaction between the electrical and mechanical modes, which may lead to destruction of the turbine shaft or loss of generators synchronization. This phenomenon is known in power systems literature as subsynchronous resonance (SSR) phenomenon. SSR can be defined as a dynamic phenomenon that exists when series capacitor compensation is used in a power system [1].

The first SSR problem was experienced in 1970 resulting in failure of a turbine-generator shaft of Mohave plant in Southern California. It was until the second shaft failure which occurred in 1971 that the real reason of the failure was known and it was called subsynchronous resonance. When a transmission line is compensated by a series capacitor, the series capacitor with the inductance of the transmission line itself forms an (LC) combination with natural frequency \( f_{er} = f_0 \sqrt{\frac{X_c}{X_L}} \), where the reactance \( X \) is defined at a frequency \( f_0 \). This frequency will appear to the rotor of the generator as a modulation of the base \( (f_0) \) frequency, so the rotor frequency \( (f_r) \) will be \( f_r = f_0 \pm f_{er} \) where \( f_0 + f_{er} \) is called super synchronous frequency and \( f_0 - f_{er} \) is called the subsynchronous frequency [2].

II. SYSTEM DESCRIPTION

The investigated system is a single machine infinite bus (SIMB), which consists of a synchronous generator with damper windings (d-q axis) connected through a transmission line, compensated by a series capacitor to infinite bus bar as shown in Fig.1-(a), which represents the electrical model of the system. Fig. 1-b shows the electromechanical mass-spring damper system. It consists of Exciter (Ex), Generator (Gen), Low Pressure (LP) and High Pressure (HP) turbine sections.

Every section has its own angular momentum (M) and damping coefficient (D), and every two successive masses have their own shaft stiffness constant (K).

The data for electrical and mechanical system are provided in reference number [3].
III. MATHEMATICAL MODEL OF THE SYSTEM

The mathematical model of the electrical and mechanical system is presented in this section. The dynamics of the generator damper windings on the q- and d-axes are included, while the effect of saturation and dynamics of the turbine governor are neglected. Using direct and quadrature (d-q) axes and Park’s transformation, the complete mathematical model describing the dynamics of the electrical and mechanical systems can be written as shown in section 3, [4]:

A. Synchronous Generator

\[
\frac{d\delta_g}{dt} = \omega_0 (\omega_g - 1) \tag{10}
\]

\[
M_g \frac{d\omega_g}{dt} = T_m - T_e - D_1 (\omega_g - 1) + K_{gq} (\delta_q - \delta_q) - K_{pg} (\delta_g - \delta_g) \tag{11}
\]

Low Pressure Turbine(LP):

\[
\frac{d\delta_2}{dt} = \omega_0 (\omega_2 - 1) \tag{12}
\]

\[
M_2 \frac{d\omega_2}{dt} = -D_1 (\omega_2 - 1) - K_{e2} (\delta_2 - \delta_2) - K_{23} (\delta_2 - \delta_3) \tag{13}
\]

High Pressure Turbine(HP):

\[
\frac{d\delta_3}{dt} = \omega_0 (\omega_3 - 1) \tag{14}
\]

\[
M_3 \frac{d\omega_3}{dt} = -D_1 (\omega_3 - 1) - K_{23} (\delta_2 - \delta_3) \tag{15}
\]

IV. THE MODEL WITH POWER SYSTEM STABILIZER(PSS) AND AUTOMATIC VOLTAGE REGULATOR(AVR)

The main function of PSS and AVR are to add more damping to the generator’s rotor oscillations by controlling its excitation using auxiliary stabilizing signal.

To cause a damping effect, the stabilizer must produce an electrical torque in phase with rotor speed deviations. Fig. (2) shows the block diagram of the PSS and AVR, which consists of three blocks [5]:

I. Phase Compensation Block.
II. Signal Washout Block.
III. Gain Block

![Fig. (2).: AVR and PSS Block Diagram Model](image-url)
A. PSS and AVR Mathematical equations:

The PSS and AVR mathematical equations are

\[ T_w \frac{dv_1}{dt} - T_d \frac{dv}{dt} = -v_1 \]  
(16)

\[ T_d \frac{dv_2}{dt} - T_k \frac{dv}{dt} = -v_2 + k_i \]  
(17)

\[ T_R \frac{dE_{fd}}{dt} = -E_{fd} + K_R (v_{ref} - E_r) \]  
(18)

V. SIMULATION RESULTS:

A. Simulation Results for the System without AVR and PSS

The power system described earlier was programmed with fifteen first-order differential equations, generated by varying the value of mechanical torque. This causes variation in the system stability which can be disclosed by evaluating the Eigenvalues.

By selecting the compensating factor, the torque mechanical (tm) =0.91 per unit, and the infinite bus bar voltage (V0)=1.0 per unit while the excitation voltage of synchronous generator (e1) =1.37 per unit, the Eigenvalues of Jacobean matrix (15×15 matrix) of the system are shown in Table(1).

From Table (1), it’s clear that the system is stable, where all Eigenvalues have negative sign. As \( \mu \) increases, the system will lose its stability region at \( \mu = 0.72 \). Table (2) gives a clear picture about the instability at \( \mu = 0.73 \).

Table (1): Eigenvalues at \( \mu = 0.68 \)

[Table data]

Table (2): Eigenvalues at \( \mu = 0.73 \)

[Table data]

Fig. (3) shows the response of the system at \( \mu = 0.68 \), while Fig. (4) shows the response at \( \mu = 0.73 \), where the system is unstable and Fig. (5), clearly shows that the system is unstable at \( \mu = 0.75 \).
B. Simulation Results of the System with AVR and PSS

In this section, the case of adding Power System Stabilizer (PSS) and Automatic Voltage Regulator (AVR) to the system was investigated described earlier. The system without adding AVR and PSS has lost its stability at \( \mu = 0.72 \). After inserting the AVR and PSS, it was found that the system is unstable at \( \mu = 0.76 \). Table 3 shows the Eignvalues at \( \mu = 0.72 \), where the system is stable, but the system without AVR and PSS is unstable at the same value of \( \mu = 0.80 \) as shown in (Table 2).

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Table (3): Eignvalues at \( \mu = 0.72 \)
Fig. (6) shows the response of the system at $\mu = 0.73$, while Fig. (7) shows the response when $\mu = 0.75$, where the system is critically stable and Fig. (8), clearly that the system is unstable at $\mu = 0.80$.
VI. CONCLUSIONS

Sub-synchronous resonance phenomenon is studied by evaluating the Eigenvalues of the Jacobian matrix a single machine infinite bus system. The effect of varying the compensating factor and the effect of AVR and PSS are also considered in this study. A complete dynamic model of single machine infinite bus with AVR and PSS controller are presented.

Including the d-q axes damper windings of synchronous generator without AVR and PSS, the Eigenvalues of the (15x15) Jacobian matrix is evaluated and it is observed that the system loses stability at point $\mu = 0.72$. When using the AVR and PSS controller, the Jacobian matrix of (18x18) is analyzed and it appears that the margin of the system stability is increased and the system become unstable at point $\mu = 0.76$.

REFERENCES


