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Research Article

STABILITY ANALYSIS OF SYNCHRONOUS GENERATOR CONNECTED TO INFINITE BUS SYSTEM

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A B S T R A C T

The most common characteristics for the power plant applications include operation of generators in parallel with a utility grid, remote control operation of excitation system from the control room, manual and automatic control of the excitation and many other factors. Also, due to the increase in capacity and expansion in operating area of the power system, the power angle stability and voltage stability will reduce the stability of the power system. In order to reduce the oscillation and to improve the relative stability of the overall system, the PID controller is designed to the system.
The main objective of this paper is to analyze the excitation control and stability of the synchronous generator connected to infinite bus system with PID controller and rate feedback. The excitation control of the system is analyzed by SIMULINK model and State Space Approach (SSA) on both MATLAB. Then, the stability of the system is analyzed from bode, root locus plots by using both MATLAB and then the eigen values of the system matrix is also obtained and analyzed using both MATLAB. The responses of the excitation control and stability of the system with/without PID controller and with/without rate feedback are obtained and compared.

INTRODUCTION

With the advancement in technology there is a vast usage of electrical energy which leads to the increase in power demand. In order to meet the power demand large number of generators is used in power station. Due to expansion of operating area and increase in capacity, the stability of the power system is affected. A stable power system is one in which the synchronous machines, when perturbed will either return to their original state if there is no net change of power or will acquire a new state without losing synchronism. In general, the excitation control and stability studies are performed on the synchronous machines in order to maintain the terminal voltage of the system constant and also to maintain the system to be stable.

Synchronous generators are exclusively used for electrical power generation. The generator input is given by means of a prime mover, usually a turbine, while the excitation current is provided by the excitation control system. The excitation may be provided through slip rings and brushes by means of AC generators mounted on the same shaft. Modern excitation system usually use AC generator with rotating rectifiers, are known as brushless excitation[5].

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The different kinds of excitation methods for synchronous machine are direct-current excitation, alternating current excitation, brushless excitation and permanent-magnet excitation. The closed loop system that represents the synchronous generator with its excitation system [8] is shown in fig. 1.

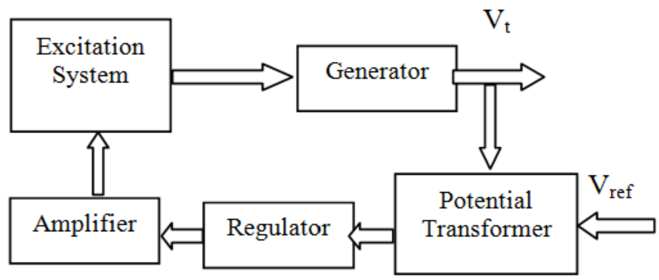

Fig 1 Synchronous generator with its excitation system

In Fig. 1, the terminal voltage of synchronous generator is given to the potential transformer which produces the change in output voltage. The regulator will generate the error voltage with respect to the reference voltage and the amplified voltage is given to the field winding of the synchronous generator. Thus, the terminal voltage is maintained more or less constant [9].

Modelling of AVR

An automatic voltage regulator (AVR) is a device used to maintain the armature terminal voltage to a predefined (reference) value. The role of AVR is to regulate the generator terminal voltage, to adjust the reactive power, to improve the power system stability and to suppress the over-voltage on load rejection. It may be designed as feed-forward or negative feedback closed loop. The main function of AVR is used to control the power output by providing the voltage level that is required and thus providing safe voltage to the equipment. The regulator will adjust the particular voltage excitation level with respect to the power system required level. The AVR system consists of amplifier, exciter, generator and sensor.

The amplifier is used to amplify the error signal which is the difference between the reference signal and the feedback signal. The transfer function of the amplifier is given by

$$\frac{X_1(s)}{X_2(s)} = \frac{K_A}{1+sT_A}$$

Where X_A is the amplifier voltage ,

V_R is the reference voltage,
K_A is the amplifier gain and
T_A is the amplifier time constant.

The exciter

The transfer function of the exciter is given by

$$\frac{X_2(s)}{X_3(s)} = \frac{K_E}{1+sT_E}$$

Where V_E is the exciter voltage,

V_A is the amplifier voltage

K_E is the exciter gain and
T_E is the exciter time constant.

The generator

The transfer function of the generator is given by

$$\frac{X_3(s)}{X_4(s)} = \frac{K_G}{1+sT_G}$$

Where V_G is the generator voltage ,

V_E is the exciter voltage,
K_G is the generator gain and
T_G is the generator time constant.

The sensor

The transfer function of the sensor is given by

$$\frac{X_4(s)}{X_5(s)} = \frac{K_S}{1+sT_S}$$

Where V_F is the sensor output (feedback) voltage ,

V_G is the generator voltage,
K_S is the sensor gain and
T_S is the sensor time constant.

The AVR system of a generator [6] has the parameters as shown in Table 1.

Table 1 Parameters of AVR system

	Gain	Time constant (sec)
Amplifier	$K_A = 12.16$	$T_A = 0.1$
Exciter	$K_E = 1$	$T_E = 0.4$
Generator	$K_G = 1$	$T_G = 1$
Sensor	$K_S = 1$	$T_S = 0.05$

Thus the modeling of AVR system is done using the parameters given in the Table 1.

PID Controller

The PID controller shown in Fig.2 is a conventional controller used to improve the system stability and to reduce the steady state error. The steady state error is the difference between the desired response of the system and its actual response.

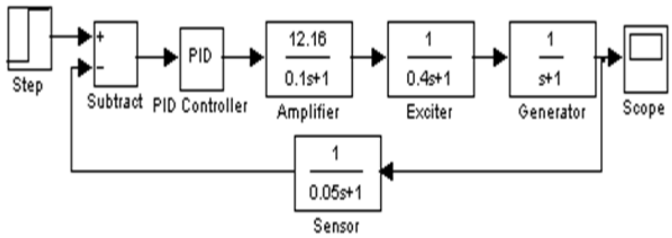

Fig 2 Simulink model of the system with PID controller using MATLAB

Tuning of PID using ZN method

The conventional methods to tune PID controller are as follows

1. Zeigler-Nichols method
2. Coon-Cohen open loop method
3. Tyreus-Luyben method
4. Auto tuning method

Of all these methods, the most commonly and widely used method is Zeigler-Nichols (ZN) method in which the PID controller parameters are tuned based on the closed loop behavior of the system. Table 2 shows the result for Z-N tuning PID.

Table 2 Tuned PID controller values for AVR system

Methods	Kp	Ki	Kd
Classical PID	0.6	1.5311	0.1633
Pessen Integral	0.7	1.9139	0.1959
Some Overshoot	0.33	1.5311	0.4354
No Overshoot	0.2	1.5311	0.4354

Based on the above result the PID controller is analyzed for its reduced error using the performance indices.

The performance index is defined as the quantitative measure to depict the system performance of the designed PID controller. The table 3 shows the performance criteria for PID controller

Table 3 Performance Criteria for PID controller

Name of the Criterion	Formula
Integral of the Absolute Error(IAE)	$IAE = \int_0^\infty \lvert e(t) \rvert dt$
Integral of Square error(ISE)	$ISE = \int_0^\infty e(t)^2 dt$

Integral of Time weighted square error(ITSE)	$\text{ITSE} = \int_0^\infty te(t)^2 dt$
Integral of the Time weighted absolute error(ITAE)	$\text{ITAE} = \int_0^\infty t\|e(t)\|dt$

Thus, these four indices are used to seek a set of PID controller values such that the closed loop system has minimum performance indices.

Stability Analysis

Stability analysis of the system is done using the bode plot and root locus plot.

Stability analysis using Bode plot

The Bode plot method gives the graphical procedure for determining stability. The open loop transfer function can be expressed in the form of magnitude and phase angle. Relative stability [8] of a closed-loop control system can be assessed by plotting its open loop transfer function by Bode plot method. The gain margin and phase margin are the two specifications used to study the relative stability of the system which can be determined from Bode plot.

The open loop transfer function of the system is given by equation 1

$$G(s) = \frac{2.382s^2 + 8.512s + 23.273}{0.04s^4 + 0.54s^3 + 1.5s^2 + s} \qquad (1)$$

Stability analysis using Root Locus plot

Stability analysis can be performed by root locus method which is a graphical method for obtaining the roots of the characteristic equation [4]. Information about the absolute stability, relative stability and transient stability can be obtained from the root locus plots. When all the roots lie on left half of s-plane the system is stable and if any of the roots lie on imaginary axis the system is marginally stable.
The closed loop transfer function of the system is given by equation 2

$$T.F = \frac{0.1191s^3 + 2.807s^2 + 9.6756s + 23.273}{0.002s^5 + 0.067s^4 + 0.615s^3 + 3.932s^2 + 9.512s + 23.273} \qquad (2)$$

Simulation Results

Excitation control analysis

The simulation of the system is done using MATLAB/SIMULINK, which is used for analyzing steady state power system stability and its capabilities for simulating transients in power systems, including control behavior.

The simulink model for the system without PID controller is shown in Fig.3. and the step response of the system is obtained as shown in Fig.4.

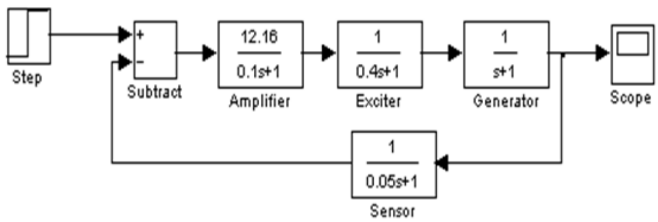

Fig 3 Simulink model of the system using MATLAB

The system response is oscillatory and unstable without the use of any controllers. Since the above system without any controller produces sustained oscillations, the PID controller is introduced to the system to enhance its performance [2]. PID controller is used to improve the transient response as well as steady state error of the system [2]. In feedback control system a controller may be introduced to modify the error signal and to achieve better control action.

Table 4 PID Tuning parameter

Methods	ISE	ITAE	ITSE	IAE
Classical PID	0.5378	0.8968	0.2994	0.9526
Pessen Integral	0.5054	0.7713	0.2594	0.8866
Some Overshoot	0.9713	6.044	1.543	2.167
No Overshoot	1.601	11.86	4.088	3.25

Table 5 Performance indices of AVR system

Methods	Mp(p.u.)	Tr(Sec)	Ts(Sec)	Ess(p.u.)
Classical PID	0.652	0.2973	3.545	0.00018
Pessen Integral	0.6595	0.2726	3.3684	0.000224
Some Overshoot	0.6411	0.5585	11.6159	0.00038
No Overshoot	0.7808	21.7394	20.7773	0.000007

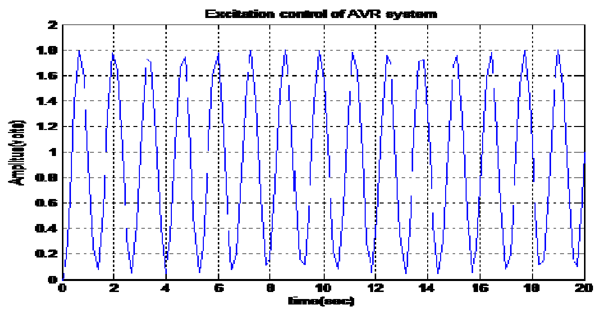

Fig 4 Oscillatory response of the system

Excitation control analysis of the system with PID controller is done using MATLAB SIMULINK model and the parameters such as peak overshoot, rise time, settling time and steady state error are compared as shown in table 4.

The PID controller is tuned using Ziegler Nicholas Method [6] and the values of Kp, Ki, Kd are obtained as shown in Table 4. Also the step response of AVR system is shown in Fig.5

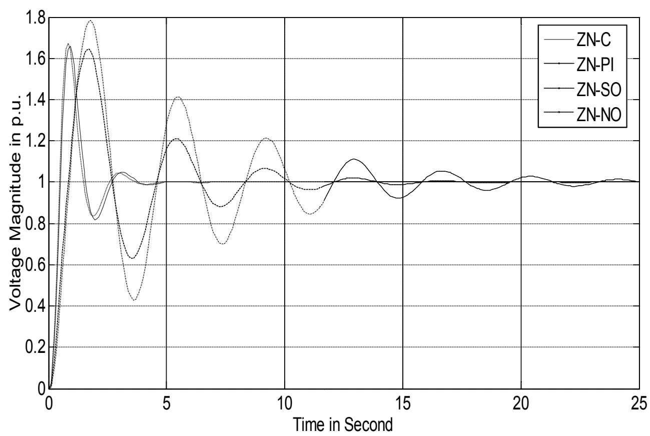

Table 5 shows the the optimal selection of PID controller is done based on the performance indices as shown in Table 3.
From the above table, it is noted that the Pessen Integral method of tuning PID for the system has a better response with the minimum performance index.It is clearly noticed from the above result that the system response is improved by using the PID controller.

State Space Analysis [7] is the modern method which is used to determine the concept of total internal states by considering all the initial conditions. The state space approach is best suited to reduce the complexity of mathematical expressions. It can be applied to non linear as well as time varying systems. It can be conveniently applied to multiple input and multiple output systems. Fig.6 shows the Step response of the system with Pessen Integral tuned PID controller. The internal states of the system is given by

$$A=\begin{bmatrix} 1.0e+004* & & & & \\ & & & & \\ -0.0034 & -0.0308 & -0.1966 & -0.4756 & -1.1637 \\ 0.0001 & 0 & 0 & 0 & 0 \\ 0 & 0.0001 & 0 & 0 & 0 \\ 0 & 0 & 0.0001 & 0 & 0 \\ 0 & 0 & 0 & 0.0001 & 0 \end{bmatrix}$$

$$B=\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}; C=\begin{bmatrix} 1.0e+004* & & & & \\ & & & & \\ 0 & 0.0060 & 0.1404 & 0.4838 & 1.1637 \end{bmatrix}$$

D =[0]

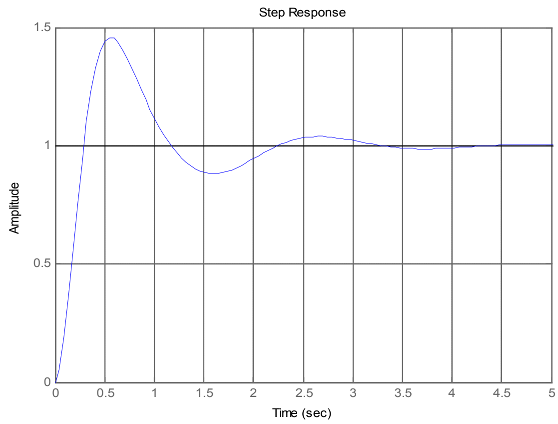

Fig 6 Step response of the system with Pessen Integral tuned PID controller using state space approach

Stability Analysis

The stability analysis of the system is done for the open loop and closed loop system using bode plot and root locus plot in MATLAB M-file editor [3].

The open loop transfer function is used to determine the gain margin and phase margin and the response of the system is shown in fig 7.

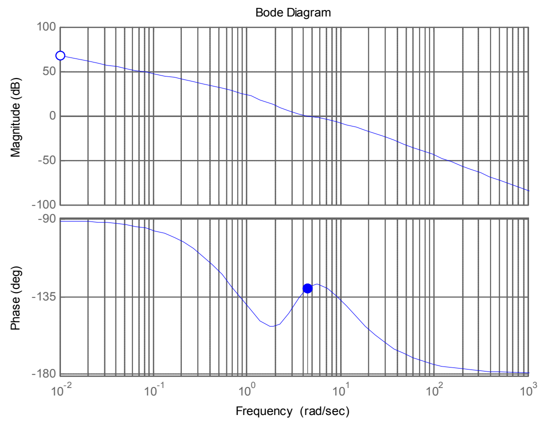

Fig 7 Stability analysis using Bode plot

The root locus plot uses closed loop transfer function to determine the stability of the system by analyzing zeroes and poles of the system.

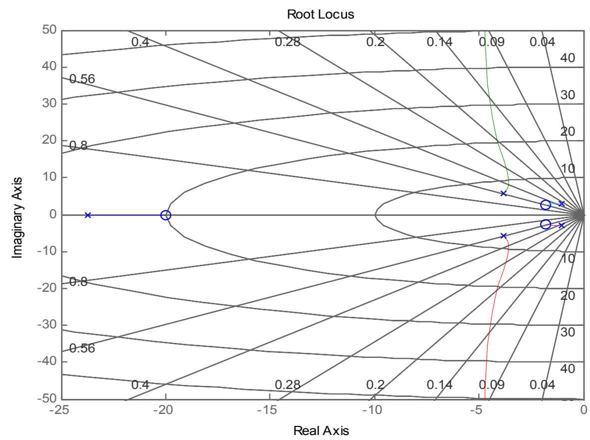

Fig 8 Stability analysis using root locus plot

From the root locus plot, the roots of the system consist of poles as -23.7, -3.85+5.87 i, -3.85-5.87 i, -1.05+2.98 i, -1.05-2.98 i and zeroes as -20, -1.79+2.56 i, -1.79–2.56 i. Thus the system is stable as all the roots lie on left half of s-plane.

CONCLUSION

In this paper, the excitation control and stability of synchronous generator connected to infinite bus system has been investigated using MATLAB. The AVR system without PID controller and rate feedback was simulated and found that the system was oscillatory and unstable. In order to improve the system response, PID controller and rate feedback were introduced in the system. Then the satisfactory response was obtained by SIMULINK and State Space Approach using MATLAB.

Then, the stability of the system with PID controller and rate feedback was analyzed from the eigen values of the system matrix which was obtained by State Space Approach using MATLAB. It was found that the eigen values were negative and hence the system was stable Then the stability of the system was analyzed by various types of plots such as Bode and Root locus plots for different values of gain using MATLAB and it was observed that the system was stable in the gain range of 1 to 71. It can be concluded from the above analysis that the inclusion of PID controller and rate feedback to the system improves its performance.

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