Frequency Domain Analysis of IMC Tuned PID Controller for Synchronous Generator Excitation System

K. Anil Naik

Abstract— **In this paper PID controller with Internal Model Control (IMC) tuning method for excitation system of the Synchronous Generator is presented with frequency domain analysis. The IMC has a single tuning parameter to adjust the performance and robustness of the controller. The proposed tuning method is very efficient in controlling the overshoot, stability and the dynamics of the excitation-control system of the Generator. The results of the IMC tuning method have been compared in the midst of controller with singular frequency (SF) based tuning and Ziegler-Nichols (Z-N) closed loop tuning. A remarkable improvement in stability of the system has been observed with IMC tuning justifying its applicability. Simulated results given in the paper show the feasibility and versatility of the IMC tuning technique in Synchronous Generator excitation system**

Index Terms— Controller; Internal Model Control; Generator; Speed; Stability; Tuning.

I. Introduction

In the power system maintaining the terminal voltage and guaranteeing the stable operation of the synchronous generator are basic requirements for safe and economical operation of the power system. Synchronous generator excitation control system is one of the most important parts of power system. It can reduce the fluctuation of the voltage; balance the distribution of inactive power and stable operation of the system. Research on the excitation control is of great importance [1, 2].

PID control is the most common one in excitation control. As it has the characteristics of simple structure, convenient debugging, strong adaptability and good robustness, it's one of the most widely used control schemes system and it comes in different forms [3-5]. And also due to its efficient and robust performance with a simple algorithm, the PID (proportional, integral, and derivative) controllers have been widely accepted in most of the industrial applications [6-10]. Ziegler and Nichols have implemented and published their classical methods and also a lot of research is done along the conventional PID controller design [11]. A recent development of modern control system enables us to combine the PID controller with various simple control algorithms in a quick and easy manner to enhance the control performance. However, the classic tuning methods involved in PID controller suffers with a few systematic design problems.

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Hence, in order to compensate these internal design problems, internal model control (IMC) based tuning approach has been developed. Due to its simplicity, robustness, and successful practical applications it gained a widespread acceptance in designing the PID controller in process industries [12-16]. The analytical method based on IMC principle for the design of PID controller is also developed [17, 18]. The resulting structure of the control system is capable of controlling a fast dynamic process by integral control, which results in a striking improvement in performance. Its advantage is even being implemented in many of the industries. However, it has been found from the literature that the IMC-PID controller has not yet been implemented in the excitation control system of Synchronous Generator. Consequently, the present work is a step towards implementing an IMC tuning based PID controller in Generator excitation system. The results with IMC tuned controller have been found to outperform the SF and Z-N tuned PID controllers.

II. MATHEMATICAL MODEL OF GENERATION EXCITATION SYSTEM

A. *Transfer function of generator unit*

As the generator's transfer function is relatively complex, here we just research on the no-load running condition when the current flowing through the stator winding i_G is zero. So only the excitation voltage u_f s effect on the generator voltage u_G should be considered. Considering the maximum voltage is near the rated voltage, the saturation situation can be ignored. From the generator's no-load air gap line and the relations existing in excitation circuit, we have [2]

$$u_{G0} = K'_G i_f \quad (1)$$

$$u_f = R_f i_f + L_f \frac{di_f}{dt} = R_f (i_f + T'_{d0} \frac{di_f}{dt}) \quad (2)$$

Where u_{G0} and i_f are generator's no-load voltage and its corresponding excitation current respectively, $K'_G = \frac{u_{G0}}{i_f}$ is a coefficient with resistance dimension, R_f and L_f are the resistance and reactance of the field winding respectively, and $T'_{d0} = \frac{L_f}{R_f}$ is the time constant of excitation circuit. By transforming "Eq. (1) and (2)" into Laplace form in zero state, we get

$$U_{G0}(s) = \frac{K_G}{1 + T'_{d0}s} U_f(s) \quad (3)$$

where $K_G = \frac{K'_G}{R_f}$ is a dimensionless coefficient. Therefore, the generator's transfer function is

$$G_G(s) = \frac{K_G}{1 + T'_{d0}s} \quad (4)$$

B. Transfer function of voltage measurement unit

Voltage measurement unit is composed of measuring transformer, rectification circuit, filter circuit and other components. Generator's three-phase terminal voltage measured by the voltage transformer first steps down by measuring transformer, and then through rectification circuit and filter circuit is converted to a smooth DC voltage which is in proportion to generator terminal voltage [19]. Therefore, the transfer function of voltage measurement unit can be approximately described as a first order lag element:

$$G_R(s) = \frac{K_R}{1 + T_R s} \quad (5)$$

Where T_R , the time constant of measurement unit, is about tens of milliseconds

C. Transfer Function of Power Amplifier Module

In self-shunt excitation systems, after the step-down of the excitation transformer and the rectification of the thyristor rectifier, generator terminal voltage supplies the power of field winding. The terminal voltage level is regulated by controlling the trigger angle of thyristor rectifier circuit. And the phase shifting circuit is generally triggered by the cosine phase [20, 21]. Based on the analysis above, we have

$$u_f = 1.35u_2 \cos\alpha = 1.35K_e u_G \cos\alpha \quad (6)$$

$$u_c = u_{tb} \cos\alpha = K_{tb} u_G \cos\alpha \quad (7)$$

Where u_f is the effective value of rectifier's output DC voltage, u_2 is the effective value of excitation transformer's secondary voltage, $K_e = \frac{u_2}{u_G}$ is the ratio of the excitation transformer, u_c is the control voltage which is the output of PID controller, u_{tb} is the peak of the synchronous voltage which is acquired by synchronous transformer, $K_{tb} = \frac{u_{tb}}{u_G}$ is the ratio of the synchronous transformer, and α is the trigger angle of thyristor rectifier circuit.

Define $K_f = \frac{1.35K_e}{K_{tb}}$ from the "Eq. (6) and (7)" we get

$$u_f = 1.35K_e u_G \frac{u_c}{K_{tb}u_G} = K_f u_c \quad (8)$$

Also considering the time delay existence between the output signal u_f and the control signal u_c , the transfer function of power amplifier module can be described as:

$$G_f(s) = \frac{K_f}{1 + T_f s} \quad (9)$$

Therefore, the transfer function block diagram of the total excitation system is shown in Figure 1.

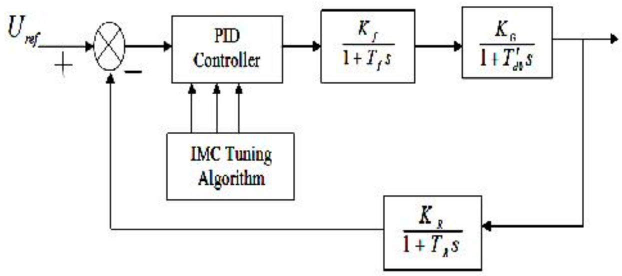

Fig. 1 Transfer Function of Generator Excitation System.

III. IMC TUNING APPROACH FOR PID CONTROLLER

Fig. 2 and 3 show the block diagrams of IMC control and equivalent classical feedback control structures, where G_P the process is, $\tilde{G}_P$ is the process model, q is the IMC controller, G_c is the equivalent feedback controller. In the IMC control structure, the controlled variable is related as[22].

$$C = \frac{G_P q}{1 + q\left(G_P - \tilde{G}_P\right)} R + \left[\frac{1 - \tilde{G}_P Q}{1 + q\left(G_P - \tilde{G}_P\right)}\right] G_D d \quad (10)$$

For the nominal case (i.e., $G_P = \tilde{G}_P$), the set-point and disturbance responses are simplified as

$$\frac{C}{R} = \tilde{G}_P q \quad (11)$$

$$\frac{C}{d} = \left[1 - \tilde{G}_P q\right] G_D \quad (12)$$

According to the IMC parameterization the process model $\tilde{G}_P$ is factored into two parts:

$$\tilde{G}_P = P_M P_A \quad (13)$$

Where P_M is the portion of the model inverted by the controller; P_A is the portion of the model not inverted by the controller and $P_A(0) = 1$. The noninvertible part usually includes dead time and/or right half plane zeros and is chosen to be all-pass.

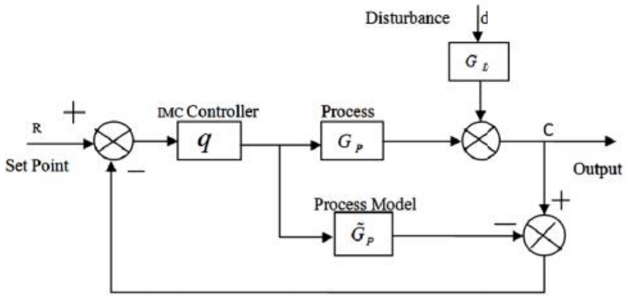

Fig. 2 IMC Structure

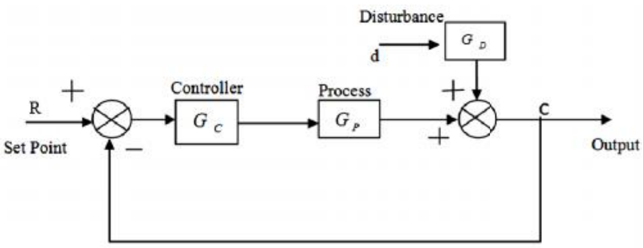

Fig. 3 Classical Feedback Control

The IMC controller is designed by

$$q = P_M^{-1} f \tag{14}$$

where the IMC filter f is usually set as

$$f = \frac{1}{\left(T_f s + 1\right)^n} \tag{15}$$

The ideal feedback controller equivalent to the IMC controller can be expressed in terms of the internal model, $\tilde{G}_P$, and the IMC controller, q

$$G_C = \frac{q}{1 - q\tilde{G}_P} = K_C\left(1 + \frac{1}{T_I s} + T_D s\right)\frac{1}{\left(1 + sT_f\right)^n} \tag{16}$$

where K , T_I and T_D are the proportional gain, integral time constant, derivative time constant of the PID controller, respectively, and T_f is the filter tuning parameters/filter time constant.

IV. RESULTS AND DISCUSSION

A standard test model as considered is taken for stability study of Synchronous Generator Excitation system with IMC tuning controller. The test model below shown is completely designed in SISO tool. Figure 4 shows the block diagram of excitation system of generator established by SIMULINK. The Synchronous generator excitation system representation includes time constant of excitation $T'_{d0} = 5s$, time constant of measurement unit T_R = 0.02s, and time constant of power amplifier module T_f =0.015s.

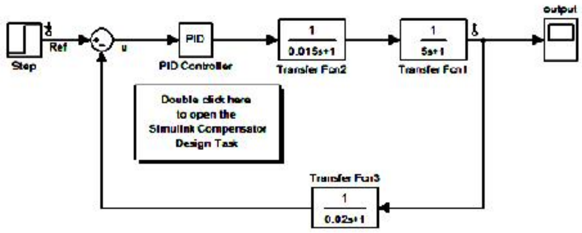

Fig. 4 The Excitation System Simulation Diagram Established by SIMULINK/SISO Tool

To show the robustness of the synchronous generator excitation system with IMC tuning controller, various cases as given below have been considered. The cases considered have been simulated and verified in SISO tool MATLAB/SIMULINK ver 7.6 [22].

Case a: Singular frequency based tuning
Case b: Ziegler-Nichols closed loop tuning
Case c: IMC based design tuning

It is mentioned here that the designed values are taken same as have been provided in [2].

4.1 *Case a: Singular Frequency based tuning*

To get the singular frequency based design tuning the Figure 4 is simulated in SISO tool. The frequency response for such a system is computed using the linear approximation (Bode plot). The magnitude and phase as a function of frequency of such a system are plotted in Figure 5.

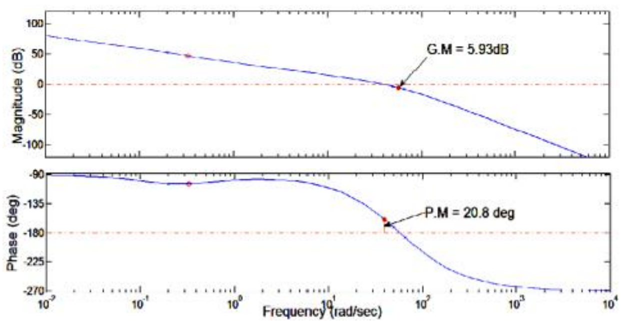

Fig. 5 Frequency response for Singular frequency based tuning

From the plotted graph the gain crossover frequency ω_{gc} is 39.5rad/sec and phase crossover frequency ω_{pc} is 57.6 rad/sec. The gain and phase margins are G_m = 5.93dB and ϕ_m = 20.8deg, ω_{gc} is less than ω_{pc} . Since ω_{gc} should not be greater than ω_{pc} for stability of the system. The excitation control system of the synchronous generator with singular frequency based tuning is stable.

4.2 *Case b: Ziegler-Nichols closed loop tuning*

To achieve such a system of speed controller PID system, the Figure 4 is simulated in SISO tool. For this system also the frequency response is computed using the linear approximation (Bode plot). The magnitude and phase as a function of frequency are plotted and is as shown in Figure 6. From Figure 6, it is determined that gain crossover frequency ω_{gc} is 35.5rad/sec and phase crossover frequency ω_{pc} is 44.9rad/sec for this case. The gain and phase margins are G_m = 3.51dB and ϕ_m = 8.89deg. Since, ω_{gc} is less than ω_{pc} and hence in this case also the synchronous generator excitation control system is stable.

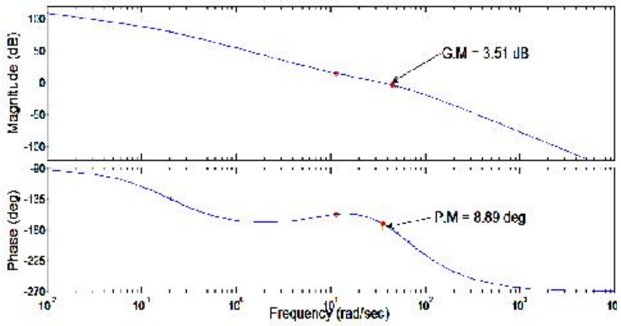

Fig. 6 Frequency response for Ziegler-Nichols closed loop based tuning

4.3 *Case c: IMC based design tuning*

This tuning design can be obtained when the Figure 4 is simulated in SISO tool. The magnitude and phase as a function of frequency for this case are plotted in Figure 7**.** It is seen from the figure that gain crossover frequency ω_{gc} is 14.2rad/sec and phase crossover frequency ω_{pc} is 57.6rad/sec. The gain and phase margins are G_m = 17.7dB and ϕ_m = 61.5deg. Since ω_{gc} is less than ω_{pc} (phase crossover frequency) then the magnitude and phase values of the bode plot are more and positive. In this case the gain margin and phase margin are more than SF and Z-N tuning methods and hence the excitation controller of generator system with IMC tuning is more stable.

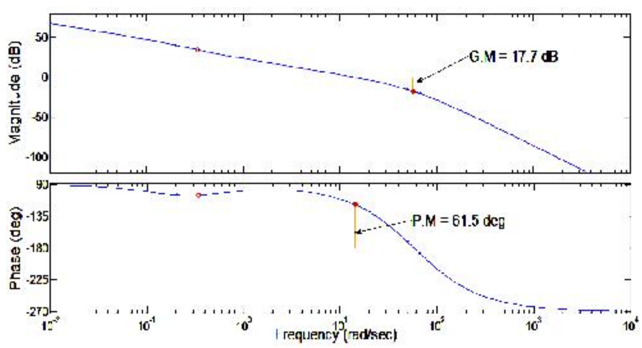

Fig. 7 Frequency response for IMC based design tuning

gain margin and 61.5^o phase margin. These are obtained from the frequency response of the open-loop system and are as given in Fig. 7. It is found from Fig. 7 that the phase margin is significantly improved at the critical frequency of inter-area modes between 14.2rad/sec and 57.6rad/sec. On the other hand, 5.93dB and 3.51dB gain margins for the Singular Frequency and Ziegler-Nichols tuning controllers are obtained which are quite low compared with the IMC tuning controller. Detailed results are as summarized in Table I.

TABLE I
FREQUENCY DOMAIN RESULTS

Specifications	Ziegler-Nichols Tuning	Singular Frequency Based Tuning	IMC Based Tuning
Gain Margin	3.51dB	5.93dB	17.7dB
Gain crossover Frequency	35.5r/s	39.5r/s	14.2r/s
Phase margin	8.89 ^{o}	20.8 ^{o}	61.5 ^{o}
Phase crossover Frequency	44.9r/s	57.6r/s	57.6r/s
Bandwidth	9.4r/s	18.9r/s	43.4r/s

V. CONCLUSION

A new robust IMC tuning based PID controller is proposed for synchronous generator excitation control system. The proposed tuning method has been found to enhance the stability of the excitation system. Different cases have been considered and compared to justify the suitability of the IMC tuning PID controller. From Table I it is found that the gain margins IMC tuning controller is 11.77dB higher compared with SF tuning controller and 14.19dB higher when compared with Z-N tuning controller.

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