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Delay Dependent Stability Analysis of Generator Excitation Control System

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Abstract

In this paper the stability of AVR system, including a stabilizing transformer, is analyzed taking into account the delays that occur during its real-time application. Time Delays are inevitable in systems involving control loops due to their effect on the stability and dynamic performance of the system. The stability analysis is performed using the Frequency Sweeping Algorithm - a control algorithm based on the frequency domain approach. The algorithm is run for distinct sets of controller gains and the delay margin is computed. These results are compared with the results obtained through simulations performed on MATLAB/SIMULINK.

Keywords: Delay margin, generator excitation control system, Frequency Sweeping Technique, Time delays.

INTRODUCTION

This paper investigates the stability of a Generator Excitation Control System considering time delays. For any change in the load, Automatic Voltage Regulator (AVR) maintains the output voltage magnitude of a generator in the acceptable limits [1].

The schematic diagram of generator excitation control system (figure.1) consists of the following: exciter, generator, voltage transducer, Phasor Measurement Unit (PMU), rectifier, stabilizing transformer and regulator.

The generator field winding is excited by the exciter and the generator output voltage magnitude is sensed by the voltage transducer. The sensed voltage is converted into phasor information by the PMU. The terminal voltage of the generator is rectified and filtered to a DC quantity by the rectifier. The regulator consists of the PI controller and the amplifier. The stabilizing transformer helps in the quick damping of oscillations by providing an additional signal to the PI controller [2].

The use of a Phasor Measurement Unit introduces time delays to the system. These time delays may be in a range of 0.5-1.0s [3-5]. The PMU introduces two types of delays:

i) Voltage transducer delay

ii) Processing Delay

These time delays affect the dynamic performance and stability of the system. Their impact is analyzed using delay margin as the performance index. Delay margin is the time-delay beyond which the system loses its stability and it can be determined by various means [6-14].

There are two methods to analyze the stability of a time delayed system:

i) Time domain approach.

ii) Frequency domain approach.

Most works reported in previous literature use time-domain approach to determine the delay margin [15, 16,20]. This paper describes the use of a control algorithm based on frequency-domain approach to determine the delay margin for measurement and communication delays while assuming that a delay-free system is stable. The theoretical delay margin values obtained from the proposed Frequency Sweeping Algorithm are tabulated for distinct sets of controller gains for two cases - with and without a stabilizing transformer. The Simulation is carried out on the AVR model using MATLAB/SIMULINK for the same set of controller gains, for both the above cases. The results from the theoretical computation are compared with the values obtained through simulation.

This paper includes the description of a dynamic model of the AVR with time delays in section II, the stability analysis using frequency sweeping method in section III, the theoretical results and its verification using simulation studies in section IV.

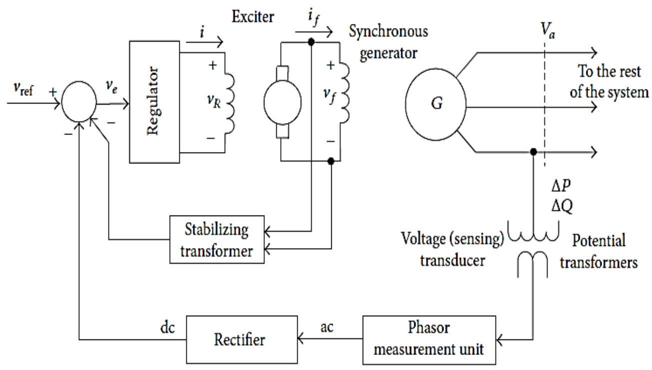

Figure 1. Block Diagram of Generator Excitation Control System

DYNAMIC MODEL OF AVR WITH TIME DELAY

This section primarily gives the transfer functions of each element that is a part of the AVR model. Linear models are generally used to analyze the dynamics of excitation control systems. Figure 2 represents the block diagram of an Excitation Control System with Stabilizing Transformer and time delay [20].

The exponential term ($e^{-s\tau}$) in the feedback path in Figure 2 represents the measurement and communication delays and it is assumed to be a constant. The following are the 1st order transfer functions for the elements of the Excitation Control System

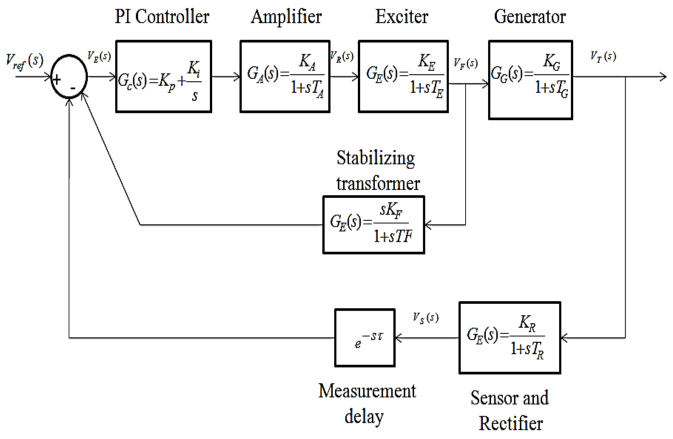

Figure 2: Excitation Control System with Stabilizing Transformer and time delay - Block diagram

The transfer function of the amplifier ,

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

The transfer function of the exciter ,

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

The transfer function of the generator ,

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

The transfer function of the sensor ,

$$G_R(s) = \frac{K_R}{1 + sT_R}$$

Where,

K_A, T_A – Amplifier's gain and time constant respectively.

K_E, T_E – Exciter's gain and time constant respectively.

K_G, T_G – Generator's gain and time constant respectively.

K_R, T_R – Sensor's gain and time constant respectively.

In order to improve the dynamic performance of the Excitation Control System, a Stabilizing Transformer is added to the system. It modifies the open loop Transfer Function of the Excitation Control System by adding a zero and thereby increasing the relative stability of the same.

The transfer function of the Stabilizing Transformer can be written as ,

$$G_F(s) = \frac{sK_F}{1 + sT_F}$$

Where, K_F, T_F are the gain and time constant of the Stabilizing Transformer respectively.

The PI controller shapes the Excitation system response and helps in achieving the desired performance. The transfer function of the PI controller can be written as ,

$$G_c(s) = K_p + \frac{K_i}{s}$$

Where K_p and K_i are the proportional and integral gains of the PI controller respectively.

DELAY-DEPENDENT STABILITY ANALYSIS

This section briefly explains the proposed control algorithm based on the frequency domain approach. The Frequency Sweeping Technique is an algorithm used for delay-dependent stability analysis and can be further employed to determine the delay margin for various sets of controller gains. This algorithm, as its name indicates, sweeps through a range of frequencies. It is known for its computational ease and accuracy.

The AVR System is assumed stable for $0 < \tau < \tau_k$ and unstable for $\tau \geq \tau_k$. For every combination of the proportional and integral gains of the PI controller, the system matrix 'A' and the delay matrix 'A_d' are determined and the delay margin values are computed using the algorithm explained below:

(i) Determine the maximum among the real parts in the eigen values of $A+A_d$ matrix. If the determined value is negative, proceed with the next step.

(ii) Find the rank of the A_d matrix .
Rank, k = The number of crossover points.

(iii) Enter the Frequency range along with its step size.

(iv) Obtain absolute values for all eigen values of $\lambda(j\omega \boldsymbol{I}$-A, $A_d)$ matrix for frequencies within the range.

(v) Attain the frequency and its corresponding angle for those absolute values that are equal to one. In the absence of absolute values that are equal to one return to (iii) and vary the range of frequency.

(vi) Calculate the delay margin τ_k using the formula –

$$\tau_k = \frac{angle}{frequency}$$

The results obtained for every combination of controller gain is tabulated. This process is followed for computations with and without inclusion of a stabilizing transformer.

RESULTS AND DISCUSSION

Theoretical Results

Table.1 comprises of the system parameters employed in the stability analysis.

The theoretical computations are made for two cases: one without the stabilizing transformer and the other with the stabilizing transformer. The system stability is investigated and the proposed method is used to find the delay margin value at the roots of the characteristic equation crossing the jω axis. Table 2. and Table 3. tabulates the results of the delay margin for different set of PI controller parameters with and without the stabilizing transformer in the AVR system.

Table 1. Parameters of AVR system

Parameters	K_E	K_A	K_G	K_R	K_F	T_E	T_A	T_G	T_R	T_F
values	1.0	5.0	1.0	1.0	2.0	0.4	0.1	1.0	0.05	0.04

Table 2. Delay margin for different sets of K_P and K^1 (with stabilizing transformer)

K_I	$\tau_d(s)$			
	$K_p = 0.1$		$K_p = 0.7$	
	Theoretical	Simulation	Theoretical	Simulation
0.2	4.055	4.06	3.65	3.645
0.4	3.243	3.24	3.256	3.252
0.6	2.9782	2.97	3.0169	3.016
0.8	2.8469	2.84	2.8929	2.89

Table 3. Delay margin for different sets of K_P and K^1 (without stabilizing transformer)

K_I	$\tau_k(s)$			
	$K_P = 0.1$		$K_P = 0.7$	
	Theoretical	Simulation	Theoretical	Simulation
0.2	0.9746	0.974	0.3385	0.3387
0.4	0.4866	0.486	0.2752	0.2756
0.6	0.2464	0.246	0.2132	0.2137
0.8	0.1076	0.1074	0.1574	0.1577

From the comparison between the Table 2. and Table 3. ,it is evident that the use of stabilizing transformer in the AVR system helps in making the system more stable by increasing the delay margin. For example, when the AVR system did not include the stabilizing transformer, for the controller gains - $K_P = 0.1$ and $K_I = 0.4$, the delay margin was found to be 0.4866s, whereas the delay margin increased to 3.243s when the stabilizing transformed was introduced . This clearly shows that the stability is improved when a stabilizing transformer is added to the AVR system

Validation of theoretical delay margin results

In order to verify the theoretical delay stability margin values attained through the Frequency sweeping algorithm, simulations are performed on the AVR model using MATLAB/SIMULINK for the same set of PI controller gains. The first set of simulations are done on an AVR model without the stabilizing transformer while the next set of simulations are performed on an AVR model with the stabilizing transformer.

For each set of controller gain, simulations are initiated from a delay-free AVR system, i.e. an AVR system with zero time delay, and the time delay is then gradually increased in steps till the AVR system becomes marginally stable. The time delay obtained at this point is termed the delay margin and any further increase in the time delay results in a purely unstable system.

Figure.4 presents the response of the AVR system with a stabilizing transformer for the controller gains K_P= 0.7 and K_I=0.8.

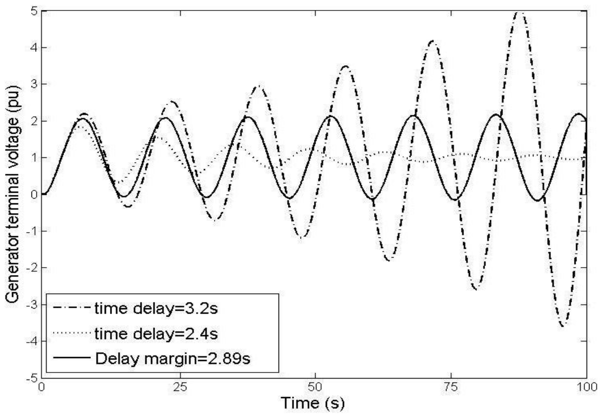

Figure 4. Time response of the system with stabilizing transformer for K_P= 0.7 and K_I=0.8

The plot with the dashed dotted lines in Fig.4 exhibits the growing oscillations for a time delay of 3.2s while the plot with the dotted lines in Fig.4 exhibits the decreasing oscillations for a time delay of 2.4s.

Therefore, the system becomes unstable when the time delay is between 2.4 s and 3.2s and that time delay corresponds to the delay margin. The plot with the solid lines in Fig.4 indicates the sustained oscillations for the time delay 2.89s, in other words, the delay margin. For time delays smaller than the delay margin the AVR system is stable while for those greater than the delay margin the system becomes unstable.

The simulated delay margin result is much closer to the theoretical delay margin (2.8929s) of the same set of controller gains (refer Table 2). Hence proved that the proposed algorithm has high accuracy.

Discussion

The tabulated values are examined and analyzed. From the tabulations it is clear that the delay stability margin increases with a decrease in the integral gain for a constant proportional gain. And an increase in the delay margin results in an AVR system of higher stability. It is also evident that an AVR system consisting of a stabilizing transformer has a higher stability when compared to an AVR system without a stabilizing transformer. The inference gained from the results obtained is that the introduction of a stabilizing transformer and the right set of controller gains will help in achieving an AVR system with an increased stability and desired damping performance..

CONCLUSION

The delay dependent stability analysis of AVR system with stabilizing transformer is done using an alternative method based on frequency domain approach. The proposed method uses the Frequency Sweeping Technique that determines the delay margin. Through simulations it is found that the system is asymptotically stable for all time delays lesser than the delay margin. The proposed method is found to be more accurate and provides better stability region with lesser computation time.

APPENDIX-I

The coefficients of polynomials P(s) and Q(s) presented in equation (1) in terms of time constants and gains of the AVR system:

$$p_6 = T_A T_E T_F T_G T_R$$

$$p_5 = T_A T_E T_F T_G + T_R (T_A T_E T_F + T_A T_E T_G + T_A T_F T_G + T_E T_F T_G)$$

$$p_4 = T_A T_E T_F + T_A T_E T_G + T_A T_F T_G + T_E T_F T_G + T_R (T_A T_E + T_E T_F + T_A T_F + T_A T_G + T_E T_G + T_F T_G + K_A K_E K_F K_P T_G)$$

$$p_3 = T_A T_E + T_E T_F + T_A T_F + T_A T_G + T_E T_G + T_F T_G + K_A K_E K_F K_P T_G + T_R (T_A + T_E + T_F + T_G + T_G + K_A K_E K_F K_P + K_A K_E K_F K_I T_G)$$

$$p_2 = T_A + T_E + T_F + T_G + K_A K_E K_F K_I T_G + K_A K_E K_F K_P + T_R (K_A K_E K_F K_I + 1)$$

$$p_1 = K_A K_E K_F K_I + 1$$

$$q_2 = K_A K_E K_P K_G K_R T_F$$

$$q_1 = K_A K_E K_G K_R (K_P + K_I T_F)$$

$$q_0 = K_A K_E K_G K_R K_I$$

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