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A Discrete Delay N-decomposition Approach for Delay-Dependent Stability of Generator Excitation Control System with Constant Communication Delays

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ABSTRACT

This paper deals with problem of delay in stability analysis of network controlled generator excitation system. Delays exist in communication channel in network based control between system and controller. A discrete delay N-decomposition is used to compute delay margin for generator excitation system with constant delay which is easier when compared to analytical method. A Lyapunov krasovskii function is constructed for given time delay generator excitation system and linear matrix inequalities techniques are used. Generator excitation system is employed with proportional integral controller, delay margin calculated for various values of gain of proportional integral controller. Theoretically obtained results are verified using simulation studies.

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1. INTRODUCTION

In Power system control one of method is employed to limit the variation in magnitude of voltage and reactive power control is done using generator excitation method. Generator excitation system (GES) involves exciter supplying DC power to field of synchronous generator [1-2]. Regulator involves proportional integral (PI) controller and amplifier. PI controller provides dynamic performance and reduces steady state error [3]. Generator terminal voltage decreases due to excessive reactive power drawn by connecting heavy inductive loads. Under such a condition change in terminal voltage is sensed by potential transformer and phasor measurement unit (PMU). PMU deliver positive sequence of voltage to rectifier and filter. DC signal from rectifier is send through communication network to the controller [4].

Controller processes this information by comparing with reference. Then send back to the GES through same network. Stability of GES is maintained by proper tuning of PI controller [4-5]. In general control system PI controller is tuned with zero delay but network based control system involves tuning of PI controller with respect to delays. These paper deals with effect of delay in generator excitation control system. Communication delay happens when bit of data travelled from GES system to the controller and controller to GES system. Network based control of GES system involves delay in feedback path as well as forward path. These delay would degrade dynamic performance GES system. There are two approaches for ascertaining stability of the time delay system.

They are Delay-independent stability criteria and delay-dependent stability criteria. Delay-independent stability criteria does not take into account of delay. Since any practical system cannot be stable for any magnitude of time-delay, this method is more conservative. Delay-dependent stability criteria gives upper bound of the time delay within which the delayed system remains stable. Hence, this method is less conservative. This criteria is derived based on Lyapunov Krasovski stability analysis [8]. Delay-dependent stability of GES is examined by Lyapunov-krasovskii functional (LKF) analysis which is less conservative. Delay margin is computed by solving chosen LKF for considered time delay system.

Delay margin is defined as maximum upper bound of delay within which closed loop system remains asymptotically stable. Delay margin is calculated for various values of K_P and K_I of PI controller [9-10]. This method can be used for tuning PI controller of GES. GES is modeled in state space equation with time delay. Many literatures discussed performance of GES with respect to delay using analytical method to determine delay margin of GES system [11-12]. These method provide accurate results but when system topology get altered it becomes afresh [4]. This motivated present research work. This problem can be eliminated by using discrete delay N-decomposition approach. It involves dividing discrete delay interval into several N-sub interval. When N increases, results becomes less conservative [14]. This paper discuss application of discrete delay N-decomposition approach for stability analysis of generator excitation system with constant delays.

2. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

The block diagram of generator excitation system is shown in Figure 1. In this figure, delay exist between sensed signal from GES and controller is τ_1. Delay exists between control signal from controller to GES is τ_2. This two delay are combined as single delay $\tau = \tau_1 + \tau_2$. The mathematical model of GES is modeled in state space framework. The V_{ref} is set to zero. The state vector of GES is $x(t) = [\Delta V_R(t) \quad \Delta V_F(t) \quad \Delta V_T(t) \quad \Delta V_S(t) \quad \int \Delta V_S(t)dt]^T$.
The state equation of delayed system is given by

$$\dot{x}(t) = Ax(t) + A_d x(t-h) \tag{1}$$

$$x(t) = \Phi(t), \;\; t \in [-max\, h, 0] \tag{2}$$

where $x(t) \in R^n$ is the state vector, $B \in R^{n\times 1}$ is input matrix, $K \in R^{1\times n}$ is controller gain, $A \in R^{n\times n}$ and $A_d \in R^{n\times n}$ represent system matrix where, $A_d = BK$, h is upper bound of constant delay.

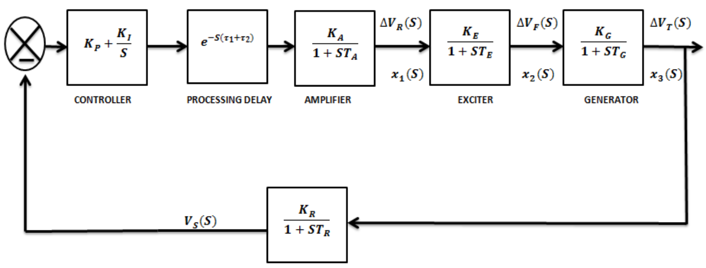

Figure 1. Mathematical model of Generator Excitation System

$$\dot{x}_1(t) = -\frac{1}{T_A}x_1(t) - \frac{K_P K_A}{T_A}x_4(t-h) - \frac{K_I K_A}{T_A}x_5(t-h) \tag{3}$$

$$\dot{x}_2(t) = \frac{K_E}{T_E}x_1(t) - \frac{1}{T_E}x_2(t) \tag{4}$$

$$\dot{x}_3(t) = \frac{K_G}{T_G}x_2(t) - \frac{1}{T_G}x_3(t) \tag{5}$$

$$\dot{x}_4(t) = \frac{K_R}{T_R}x_3(t) - \frac{1}{T_R}x_4(t) \tag{6}$$

$$\dot{x}_5(t) = x_4(t) \tag{7}$$

The above equations are represented in standard format (1) given below

$$\begin{bmatrix}\dot{x}_1(t)\\ \dot{x}_2(t)\\ \dot{x}_3(t)\\ \dot{x}_4(t)\\ \dot{x}_5(t)\end{bmatrix}=\begin{bmatrix}-\frac{1}{T_A} & 0 & 0 & 0 & 0\\ \frac{K_E}{T_E} & -\frac{1}{T_E} & 0 & 0 & 0\\ 0 & \frac{K_G}{T_G} & -\frac{1}{T_G} & 0 & 0\\ 0 & 0 & \frac{K_R}{T_R} & -\frac{1}{T_R} & 0\\ 0 & 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\\ x_3(t)\\ x_4(t)\\ x_5(t)\end{bmatrix}+\begin{bmatrix}0 & 0 & 0 & -\frac{K_PK_A}{T_A} & -\frac{K_IK_A}{T_A}\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\end{bmatrix}\begin{bmatrix}x_1(t-h)\\ x_2(t-h)\\ x_3(t-h)\\ x_4(t-h)\\ x_5(t-h)\end{bmatrix} \quad (8)$$

The parameters are $K_A = 5$, $K_E = 1$, $K_G = 1, K_R = 1$, $T_A = 0.1, T_E = 0.4$, $T_G = 1$, $T_R = 0.05$ [11-12]. Delay margin is obtained by solving theorem 1. Condition for maximum delay is $0 \le \tau \le h$.

3. THEOREM

The delay-dependent stability of consider time delay GES is given (1) and (2) Theorem 1 [14]. For a given scalar $h > 0$ and a positive integer $N \ge 2$, the system is asymptotically stable if there exist real $n \times n$ matrices $P > 0$, $Q > 0$, $R > 0$, $W \ge 0$ and $S_{ii} = S_{ii}^T(i = 1,2 \ldots .N)$, $S_{ij}(i < j; I = 1,2 \ldots . . N-1;$ $j = 2,\ 3 \ldots \ldots N)$ such that

$$S = S^T = \begin{bmatrix}S_{11} & S_{12} & . & . & S_{1N}\\ * & S_{22} & . & . & S_{2N}\\ . & . & . & . & .\\ . & . & . & . & .\\ * & * & . & . & S_{NN}\end{bmatrix} \ge 0 \quad (9)$$

$$\omega = \begin{bmatrix}\omega^{(1)} & \omega^{(2)} & \omega^{(3)}\\ * & -W & 0\\ * & * & -R\end{bmatrix} < 0 \quad (10)$$

where

$$\omega^{(1)} = \begin{bmatrix}\omega_{11}^{(1)} & \omega_{12}^{(1)} & S_{13} & . & . & S_{1N} & PB+R\\ * & \omega_{22}^{(1)} & \omega_{23}^{(1)} & . & . & S_{2N}-S_{1N-1} & -S_{1N}\\ * & * & \omega_{33}^{(1)} & . & . & S_{3N}-S_{2N-1} & -S_{2N}\\ . & . & . & . & . & . & .\\ . & . & . & . & . & \omega_{NN}^{(1)} & -S_{N-1\,N}\\ * & * & * & . & . & * & \omega_{N+1\,N+1}^{(1)}\end{bmatrix}$$

$$\omega^{(2)} = \begin{bmatrix}\frac{h}{N}A^TW\\ 0\\ 0\\ .\\ .\\ \frac{h}{N}B^TW\end{bmatrix},\ \omega^{(3)} = \begin{bmatrix}hA^TW\\ 0\\ 0\\ .\\ .\\ hB^TW\end{bmatrix}$$

Elements of $\omega^{(1)}$

$$\omega_{11}^{(1)} = A^TP + PA + Q - W - R + S_{11}$$

$$\omega_{22}^{(1)} = S_{22} - S_{11} - W$$

$$\omega_{33}^{(1)} = S_{33} - S_{22}$$

$$\omega_{NN}^{(1)} = S_{NN} - S_{N-1\,N-1}$$

$$\omega_{N+1\,N+1}^{(1)} = -S_{NN} - Q - R$$

$\omega_{12}^{(1)} = W + S_{12}$

$\omega_{23}^{(1)} = S_{23} - S_{12}$

Theorem 1 is applied to GES to determine delay margin for constant delays. Delay margin is obtained for various values of K_P and K_I of PI controller.

3.1. Delay-dependent stability problem

Consider a LKF for given time delay system (1)

$$v(t,x_t) = x^T(t)Px(t) + \int_{t-h}^{t} x^T(\xi)Qx(\xi)d\xi + \int_{t-h}^{t} (h - t - \xi)\dot{x}^T(\xi)(hR)\dot{x}(\xi)d\xi + \int_{t-\frac{h}{N}}^{t} Z^T(\xi)Sz(\xi)d\xi + \int_{t-\frac{h}{N}}^{t} \left(\frac{h}{N} - t + \xi\right)\dot{x}^T(\xi)\left(\frac{h}{N}W\right)\dot{x}(\xi)d\xi \quad (11)$$

where $\left[x^T(t) \quad x^T(t-\frac{h}{N}) \quad . \quad . \quad . \quad x^T(t-\frac{(N-1)h}{N})\right]$

4. RESULTS AND DISCUSSION

Delay margin (h) is obtained from theorem 1 for GES for various values of gain PI controller with N (subinterval) =3, 4, 5. Table 1 gives delay margin for K_p= 0.3 to 0.9 and K_I= 0.1 to 0.5 with N=3. Table 1 and figure 4 shows delay margin (h) decreases for increase in K_I for fixed K_P. Similarly delay margin decreases for increase in K_P for fixed K_I values shown in figure 3. These inferences are used in studying PI controller in performance of network control. From table 1, 2, 3 and figure 2 shows when sub-interval N increases delay margin increases, result becomes less conservative for increase in N for considered network controlled GES.

Table 1. Delay margin of GES with N=3

K_I	K_P 0.3	0.5	0.7
0.1	1.4021	0.6239	0.3640
0.2	0.9604	0.5446	0.3340
0.3	0.6755	0.4649	0.3029
0.4	0.4820	0.3902	0.2716
0.5	0.3453	0.3229	0.2407

Table 2. Delay margin of GES with N=4

K_I	K_P 0.3	0.5	0.7
0.1	1.4083	0.6255	0.3645
0.2	0.9666	0.5457	0.3344
0.3	0.6766	0.4656	0.3032
0.4	0.4824	0.3906	0.2718
0.5	0.3455	0.3232	0.2409

Table 3. Delay margin of GES with N=5

K_I	K_P 0.3	0.5	0.7
0.1	1.4112	0.6262	0.3647
0.2	0.9678	0.5461	0.3346
0.3	0.6771	0.4659	0.3034
0.4	0.4827	0.3908	0.2719
0.5	0.3456	0.3233	0.2410

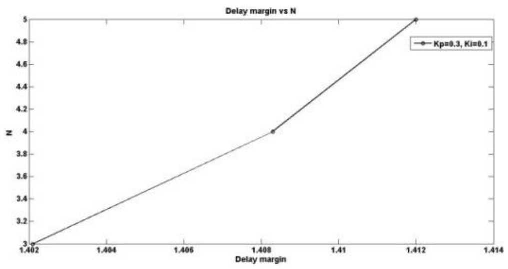

Figure 2. Delay margin vs. N(sub interval of delay) with K_P=0.3 and K_I=0.1

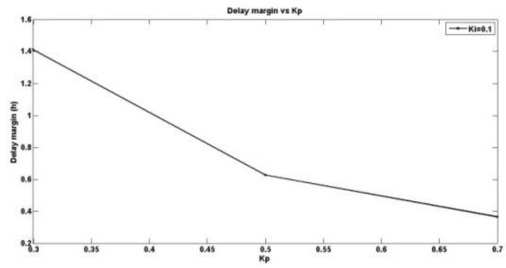

Figure 3. $K_P$vs. delay margin (h)

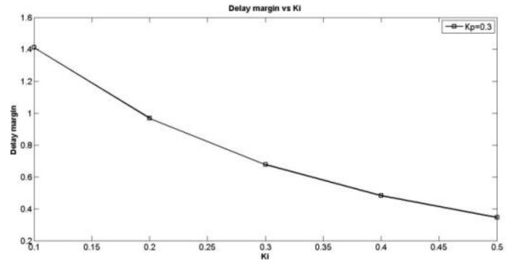

Figure 4. K_I vs. delay margin (h)

5. MATLAB SIMULATION FOR VERIFICATION OF THEORETICAL RESULTS

Simulation is done for generator excitation control system equipped with PI controller. Theoretically calculated delay margin values are used in simulation studies. For verification purpose K_P=0.3 and K_I=0.1 are chosen with N=5 from table 3. From table 3 delay margin h is chosen such that h=1.4112 s. Figure 5 shows that voltage response of GES without delay. System response reaches steady state (absolutely stable system). Figure 6 shows voltage response of GES with constant delay of 1 s throughout process. System reaches steady state with some oscillations (stable system). Figure 7 shows voltage response of GES with delay margin of h=1.4112 s. Response of system with sustained oscillations (marginally stable system). Delay margin h=1.42 and h=1.5 chosen for same value of K_P and K_I. Figure 8 and 9 shows system becomes unstable.

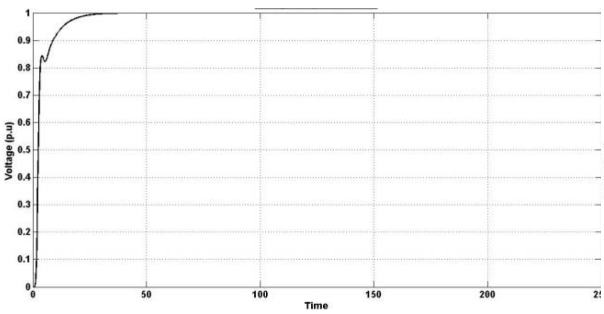

Figure 5. Voltage response of GES with zero delay

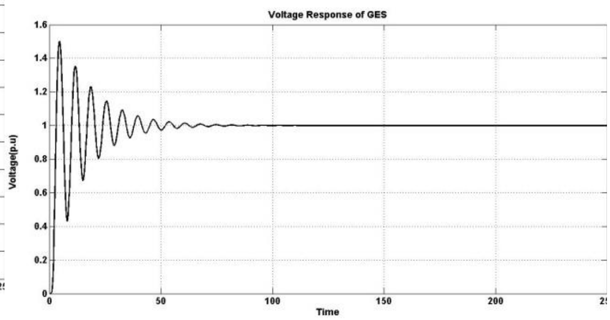

Figure 6. Voltage response of GES with delay margin h=1.0 s with K_P=0.3 and K_I=0.1

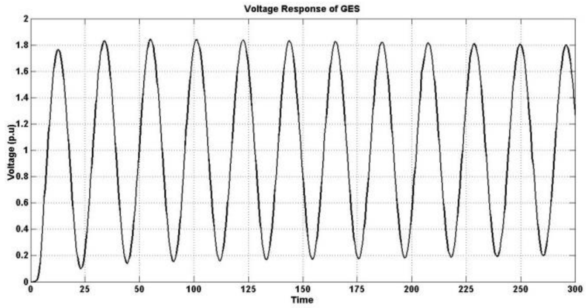

Figure 7. Voltage response of GES with delay margin h=1.4112 s with K_P=0.3 and K_I=0.1

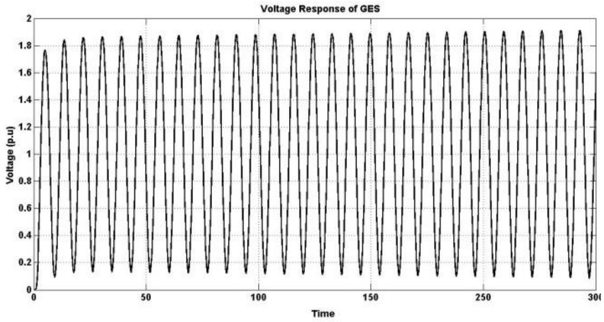

Figure 8. Voltage response of GES with delay margin h=1.42 s with K_P=0.3 and K_I=0.1

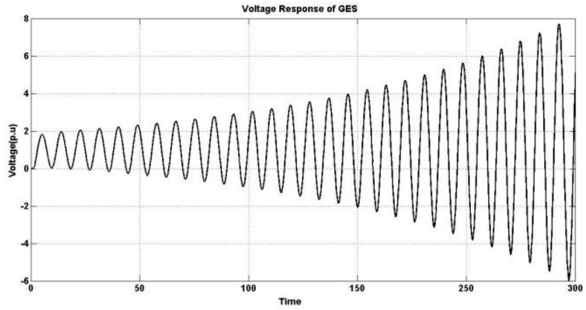

Figure 9. Voltage response of GES with delay margin h=1.5 s with K_P=0.3 and K_I=0.1

6. CONCLUSION

A Discrete delay N-decomposition approach overcomes disadvantages of exact method provided in recent literatures. This method involves dividing delay interval into N sub-intervals. When N increases, chosen LKF becomes less conservative. Such that N=5 provides sufficient conditions for system stability. Hence this method can be used to determine delay margin any systems with constant delays. This approach applied to GES for delay-dependent stability analysis for constant delays. Delay margin calculated for GES for various values of gain of PI controller. This method can be used to tune network controller to maintain system stability.

7. DECLARATION OF CONFLICTING INTERESTS

The authors declare that there is no conflict of interest

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