INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VIII August 2025

Delay-Dependent Stability Analysis of Generator Excitation Control System Using CAN Bus

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DOI: https://doi.org/10.51584/IJRIAS.2025.100800169

Received: 29 August 2025; Revised: 11 September 2025; Accepted: 15 September 2025; Published: 04 October 2025

ABSTRACT

As the times develop, the use of communication is widening and communication in control systems will play a more important role. The automation of power plants also increases the level of automation and control performance by building control systems using fieldbus. In particular, the CAN bus, which can realize real-time information sharing, allows the excitation control system, governor control system and other control systems to jointly utilize the electrical quantities of the generator, thus reducing the cost of building the system and increasing the utilization efficiency of resources. However, this allows the control system to include the time delay due to communication. Worldwide, efforts are being made to reduce the instability of excitation control systems in the presence of communication-induced time delays. This is because if the generator excitation control system contains a time delay component, the instability of the control can be increased. In this paper, using Lyapunov-Krasovskii functional approach combined with Wirtinger inequality, stability criterion in linear matrix inequality (LMI) framework is presented for ascertaining the delay-dependent stability of a generator-excitation control system using field bus. Stability analysis is carried out for excitation control system based on PI controller with time-invariant feedback loop delay. The delay-dependent stability problem is formulated by mathematical modeling of closed-loop systems such as linear delay continuous-time delay differential equations, and using LMI-based stability criteria, the maximum allowable limit of the CAN bus delay for which the closed-loop system can operate normally without losing stability is calculated for various subsets of controller parameters. The effectiveness of the proposed result is validated on a benchmark excitation control system with simulation results.

Keywords: Delay-dependent stability, Generator-Exciter Control System, Lyapunov-Krasovskii functional, CAN bus, Linear Matrix Inequality (LMI).

INTRODUCTION

In electrical power systems, a governor control and excitation control system are installed for each generator to maintain the system frequency and generator output voltage magnitude within the specified limits when changes in real and reactive power demands occur.

If the power plant automation system is constructed by the field bus as shown in Fig. 1 and the generator excitation controller and measuring device are connected by the field bus, the feedback loop of the closed-loop control system will be completed through the field bus, i.e., the communication network.

We have conducted a study to build more efficient and high-performance plant automation systems, especially hydropower automation systems.

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In this process, a plant automation system was built by CAN bus, a kind of fieldbus, in a hydro plant whose process scale is simple compared to a thermal plant, as shown in Fig. 1.

And the CAN bus features good real-time two-way data communication performance to make all the measurement data available jointly, thus reducing the cost of system construction and increasing the utilization of information resources.

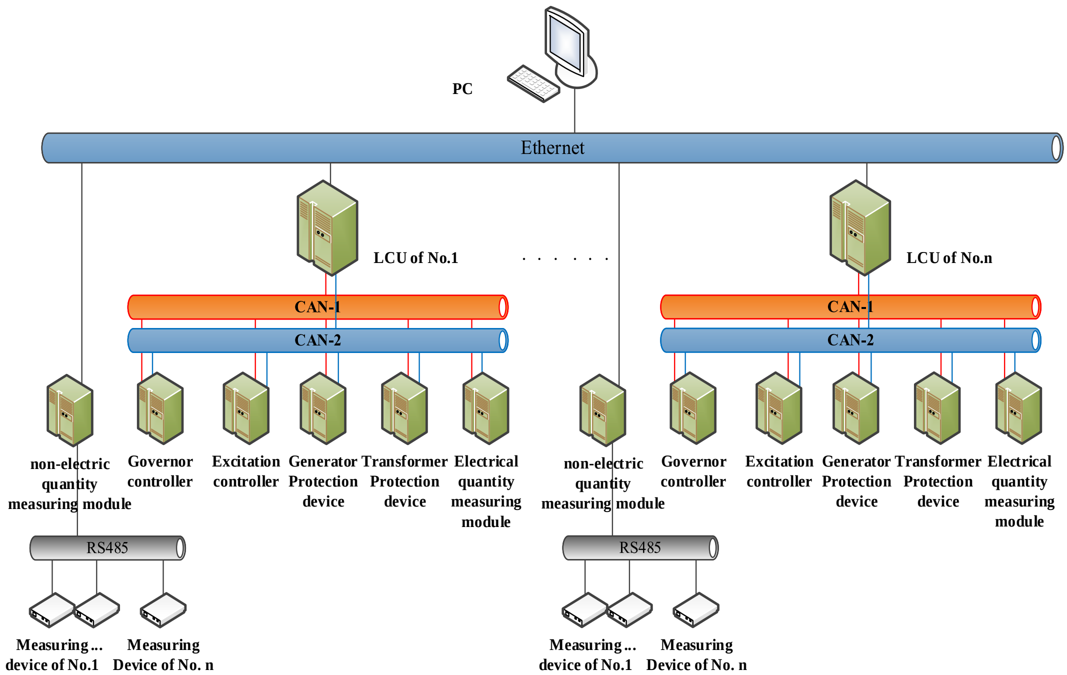

Fig. 1. Generator control system with CAN bus.

This typical field bus-based generator excitation control system consists of an exciter, a measuring device, a controller (embedded PI control logic) and an output device.

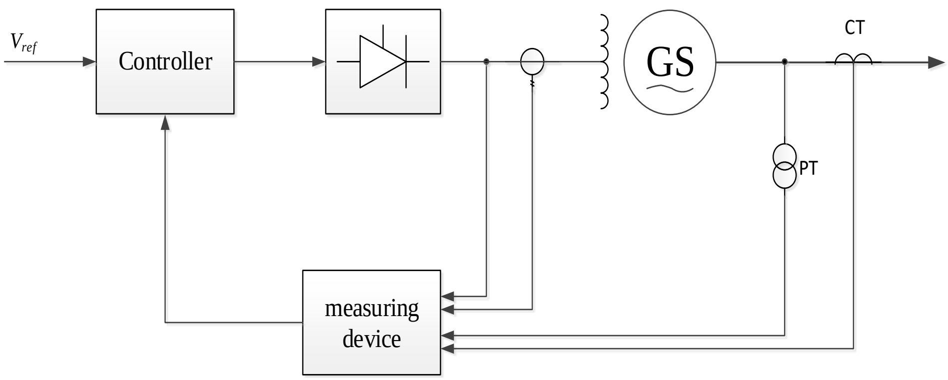

Fig. 2. a generator-excitation control system configuration for static excitation system

The generator-excitation control system should handle the event of any sudden unknown deviation in generator terminal voltage due to power system operating conditions such as excessive reactive power consumption by connected loads.

Under such perturbed operating condition, three phase potential transformer (PT) senses the generator terminal voltage and feeds it to the measuring device.

These measurement signals are transmitted as data packets to the controller via the communication network.

In the controller, the error between the reference signal and the feedback signal is computed and processed by the proportional integral (PI) control logic and produces an analog signal that controls the output gain stage.

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That is, the excitation controller controls the magnetic field of the exciter by this signal and changes the excitation voltage.

Due to the changes of excitation terminal voltage, the generator excitation current changes, and this changes of the excitation current results in the changes of the reactive power of the generator.

Therefore, reactive power generation changes to a new equilibrium point and changes the generator terminal voltage to the desired value.

The use of measurement devices by the communication network results in a time delay involving measurement delay and communication delays consisting of AD conversion delay and data processing delay.

The measurement device is a device that measures dynamic data of power systems such as voltage, current, angle and frequency and excitation voltage and current using discrete Fourier transform (DFT).

The data processing delay is the amount of time required to convert AD conversion data into vector information by DFT, and the total measurement delay is in milliseconds.

In generator control using field bus, data transmission is realized through various communication modes, such as PROFIBUS, CAN, Ethernet, etc., and means of telephone lines, fibre cables, power lines, radio etc.

Depending on the communication link used, the total communication delay is considered to be in the range of 100-700 ms [1].

The measurement and communication delays involved between the instant of measurement and that of signal being available to the controller are the major problem in the excitation control.

It is obvious that when voltage signal is measured from measurement device and transferred to the local controller, the communication delay will increase.

The PI controller, the focus of the excitation control system, is designed assuming zero delays by the communication network, but if we collect measurement data through the communication channel in which the data (control or/and measured) buffering, processing and propagation, the feedback loop delay is practically inevitable, and the delay by the communication network is time-varying in nature.

In any case, these feedback loop delays invariably pose serious limitations to achievable performance of the closed-loop system, and in some cases, may even lead to destabilizing the generator system.

The inevitable time delays in generator excitation control have a destabilizing impact on the system dynamics and lead to unacceptable performance such as loss of synchronism and instability. Therefore, they could not be ignored.

Hence, stable delay margin (i.e. maximum delay bound which the networked controlled system can accommodate without losing asymptotic stability) for such excitation control systems must be computed for various subsets of controller parameters (proportional gain K_P and integral gain K_I) through delay-dependent stability analysis procedure so that they serve as a practical guide line for fine tuning of controller parameters at the implementation stage.

This, in turn, will enable one to achieve optimal performance from the time-delayed system.

Delay-dependent stability criteria are employed to compute the stable margin for the communication delays within which the excitation control system remains asymptotically stable.

Several studies have been carried out in the literature to overcome time delay-induced instability in generator excitation control systems [9, 10].

In particular, in [10], the delay produced when the controller and generator are geographically distant and the excitation control system is controlled by the network is considered in the excitation control system proposed in [9].

In this paper, we consider the delay stability in the generator excitation control system to overcome the instability of the generator excitation control system resulting from measurement and communication delay when used for excitation control by collecting the state quantities of the generator through the CAN bus within the generator control system built by the CAN bus.

Though the results presented in these papers yield accurate delay bounds for the time-invariant feedback loop delays.

The aforesaid shortfall is alleviated in this paper, where in, a generalized criterion (sufficient condition) is presented for ascertaining delay dependent stability of excitation control systems with time invariant feedback loop delays.

In the proposed approach, the mathematical model of the PI controlled excitation control system with time-invariant feedback loop delays is developed as a linear retarded delay-differential continuous-time equation.

This state-space model is a generalized modeling framework for dynamical systems with time-delays [8].

Subsequently, based on Lyapunov-Krasovskii functional approach combined with Wirtinger inequality [12], a delay-dependent stability criterion is presented in LMI framework to compute the maximum bound of the time-delay within which the closed loop excitation control system remains asymptotically stable in the sense of Lyapunov.

The paper presented simulation results to demonstrate analytical results on delay-dependent stability.

System Description And Problem Formulation

Fig. 3 shows the closed loop configuration of the PI controlled excitation control system shown in Fig. 2.[9]

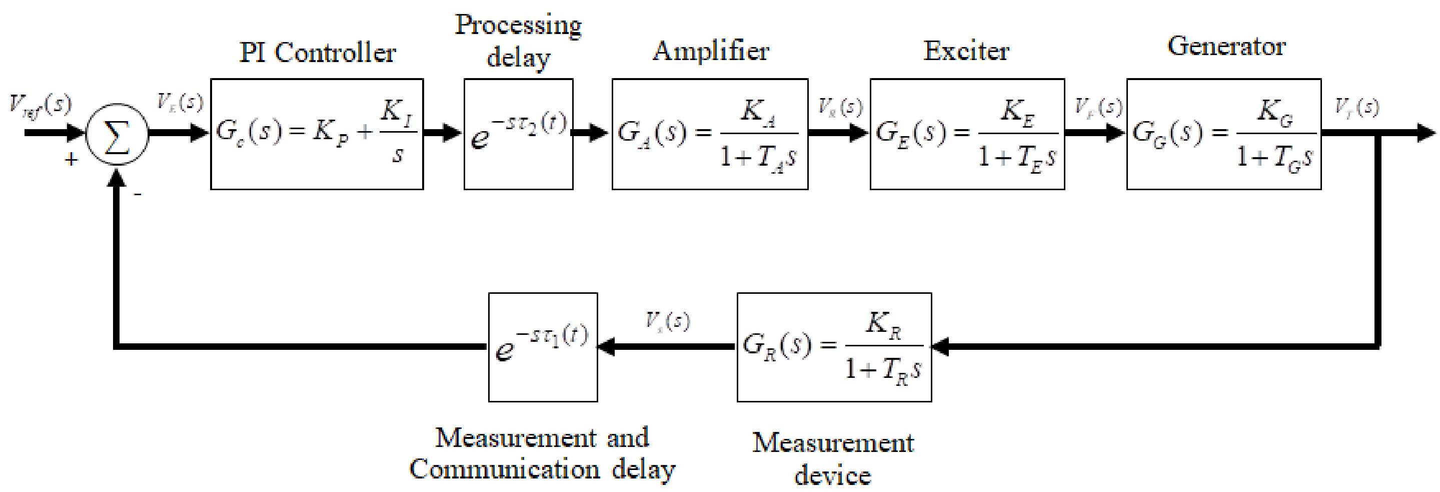

Fig. 3. Block diagram of excitation control system with communication network delays

In the figure, $\tau_1(t)$ and $\tau_2(t)$ represent the time-delays between the measurement device (sensor and Rectifier/Filter system) to controller (PI controller), and controller to the actuator (i.e. the final control element, the exciter unit) respectively.

With the assumption that both these delays are time-invariant (i.e. $\tau_1(t)=\tau_1$, $\tau_2(t)=\tau_2$, $\forall t$), they are combined into a single delay component $\tau=\tau_1+\tau_2$ in the presented stability analysis.

For mathematical modelling of the excitation control system in state-space approach, the deviation variables (of the system from the irrespective equilibrium values) are considered as state variables.

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The reference input $V_{ref}(t)$ is set to zero.

The state vector of the excitation control system is given as

$$x(t) = [\Delta v_R(t)\ \ \Delta v_F(t)\ \ \Delta v_T(t)\ \ \Delta v_S(t)\ \int \Delta v_{RS}(t)dt]^T.$$

The corresponding state space model can then be derived easily as follows:

$$\begin{cases} \dot{x}(t) = Yx(t) + Y_d x(t-\tau) \\ x(t) = \Phi(t), t \in [0, -\bar{\tau}] \end{cases} \qquad (1)$$

where $x(t) = [x_1(t), \ldots, x_n(t)]^T \in \mathbb{R}^n$ is the system state; $Y \in \mathbb{R}^{n\times n}$ and $Y_d \in \mathbb{R}^{n\times m}$ are known system matrices.

The time-delay τ satisfies the following limiting condition:

$$0 \le \tau \le \bar{\tau}. \qquad (2)$$

Being delayed system, the initial condition is expressed as a continuous-time function $\Phi(t)$ in $t \in [-\bar{\tau}, 0]$, where $\bar{\tau} = \max(\tau)$.

The problem addressed in this paper is to propose a stability criterion to validate the delay-dependent stability of the excitation control system in system (1) satisfying condition (2) using the Lyapunov-Krasovskii function method in LMI formulation.

For deriving the proposed stability criterion, following lemmas [11] and Wirtinger inequality [12] are indispensable:

Lemma 1. Jenson Integral Inequality: For any symmetric positive definite matrix $M \in R_{n\times n}$, scalars γ_1 and γ_2 satisfying $\gamma_1 < \gamma_2$, vector function $\omega: [\gamma_1, \gamma_2] \to R^n$ such that following integrals are well defined, then

$$\int_{\gamma_1}^{\gamma_2} \omega^T(s)\, M\omega(s)ds \ge \frac{1}{\gamma_2 - \gamma_1}\left[\int_{\gamma_1}^{\gamma_2} \omega(s)\, ds\right]^T M \left[\int_{\gamma_1}^{\gamma_2} \omega(s)\, ds\right]. \qquad (3)$$

Lemma 2. Wirtinger Inequality: For given symmetric positive matrix R, and for any differentiable signal ω in $[a, b] \to R^n$, the following inequality holds:

$$\int_{\gamma_1}^{\gamma_2} \dot{\omega}^T(u)\, R\dot{\omega}(u)du \ge \frac{1}{b-a}\begin{bmatrix}\omega(b)\\ \omega(a)\\ v\end{bmatrix}^T W(R)\begin{bmatrix}\omega(b)\\ \omega(a)\\ v\end{bmatrix}, \qquad (4)$$

where

$$v = \frac{1}{b-a}\int_a^b \omega(u)du,$$

$$W(R) = \begin{bmatrix} \left(1+\frac{\pi^2}{4}\right)R & \left(-1+\frac{\pi^2}{4}\right)R & \left(-\frac{\pi^2}{2}\right)R \\ * & \left(1+\frac{\pi^2}{4}\right)R & \left(-\frac{\pi^2}{2}\right)R \\ * & * & \pi^2 R \end{bmatrix},$$

where * represents symmetrical elements corresponding to upper triangular elements.

Delay-Dependent Stability Criterion Of Excitation Control System

The delay-dependent stability criterion for the system (1) satisfying (2) is stated in the following theorem:

Theorem. For a given constant delay τ, the system in (1) satisfying (2) is asymptotically stable in the sense of

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Lyapunov, if there exist real, symmetric, positive definite matrices G, H and F; symmetric matrix X and any matrix E such that following LMIs hold:

$\Pi_1(\tau) < 0,$ (5)

$\Pi_2(\tau) < 0,$ (6)

with

$$\Pi_1(\tau) = \begin{bmatrix} G & E \\ * & X + \frac{1}{\tau}H \end{bmatrix}$$

$$\Pi_2(\tau) = \Pi_2^0(\tau) - \frac{1}{\tau}W(R)$$

where

$$\Pi_2^0(\tau) = \begin{bmatrix} \Pi_{11} & GY_d - E & \tau Y^T E + \tau X \\ * & -H & \tau Y_d^T E - \tau X \\ * & * & 0 \end{bmatrix} + \begin{bmatrix} Y^T \\ Y_d^T \\ 0 \end{bmatrix}^T + \tau(R) \begin{bmatrix} Y^T \\ Y_d^T \\ 0 \end{bmatrix}.$$

where

$\Pi_{11} = Y^T G + GY + E + E^T + H.$

This theorem is proved by Lemmas 1 and 2.

The presented stability criterion (LMI) can be easily solved using Matlab.

Case Study

An excitation control system with time-invariant feedback loop delay by field bus (shown in Fig. 2) is considered to validate the proposed delay-dependent stability criterion.

Theoretical delay margin results are verified by using Matlab/Simulink.

The parameters of the given excitation control system are given below:

Table1. Parameters of excitation control System

System	Gain	Time-Constant
Amplifier	K_A=4	T_A=0.005
exciter	K_E=1	T_E=.0.2
Generator	K_G=1	T_G=1
Sensor	K_E=1	T_E=0.05

When the delay τ is made zero, the system equation (1) becomes

$\dot{x}(t) = (Y + Y_d)x(t).$ (11)

Now, it is observed that the eigen values of the system matrix ($Y+Y_d$) depend on the controller parameters K_P and K_I.

The Table 2 gives the maximum value of $K_I^*(s^{-1})$ for a fixed value of K_P for which the excitation control system is on the verge of instability, i.e. having one complex-conjugate pair of eigen values on the jω axis.[9]

Table2. Maximum integral controller gain for a given K_P

State No.	K_P	$K_I^*(s^{-1})$
1	0.1	0.681
2	0.2	0.874
3	0.3	1.049
4	0.4	1.206
5	0.5	1.347
6	0.6	1.468
7	0.7	1.571
8	0.8	1.654
9	0.9	1.720
10	1.0	1.763

For K_P=0.7 and K_I=0.8s^{-1}, the evolution of the incremental variable $\Delta v_T(t)$ versus t for a per-unit perturbation in the generator terminal voltage is shown in Fig.4.

From the figure, it is clear that for the chosen values of the controller parameters, the delay-free excitation control system is asymptotically stable.

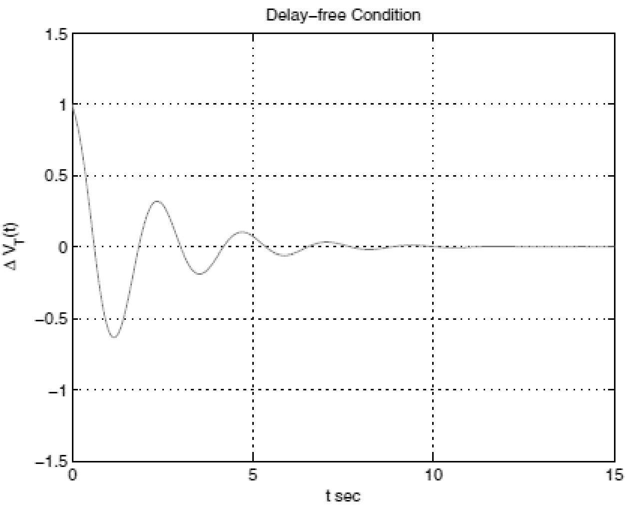

Fig.4. Evolution of $\Delta v_T(t)$ under zero delay condition.

Now, in the presence of communication delay, the maximum delay bound provided by Theorem for different values of K_P for K_I=0.5s^{-1} and K_I=0.65s^{-1} are given in Table 3; the Fig. 5 shows the corresponding variation.

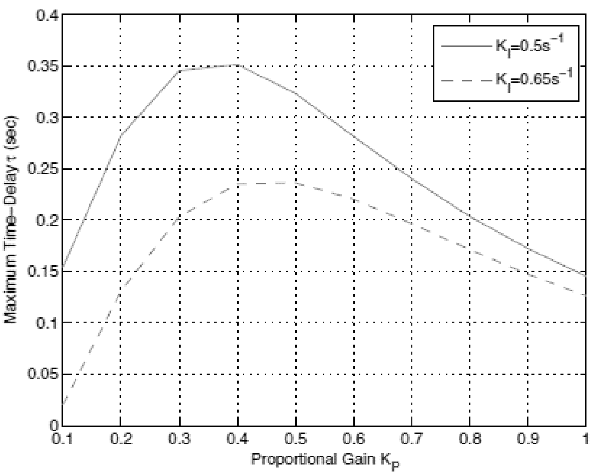

Fig.5.Variation of Maximum Time Delay with K_P.

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From the figure, it is clear that as the proportional gain K_P increases for a given value of K_I, the time delay initially increases, and after reaching a peak value, it starts decreasing with increasing K_P.

Table 3. Maximum delay bound for given K_P and $K_I(s^{-1})$

State No.	K_P	$K_I=0.5(s^{-1})$	$K_I=0.65s^{-1}$
1	0.1	0.147	0.020
2	0.2	0.269	0.146
3	0.3	0.327	0.193
4	0.4	0.348	0.245
5	0.5	0.331	0.237
6	0.6	0.286	0.231
7	0.7	0.251	0.202
8	0.8	0.213	0.181
9	0.9	0.182	0.157
10	1.0	0.152	0.136

The maximum delay bound for different values of K_I for a fixed values of K_P (K_P=0.1, K_P=0.3, K_P=0.5, K_P=0.7, K_P=0.9) provided by Theorem are given in Table 4.

Table 4. Maximum upper delay bound

$K_I(s^{-1})$	Maximum Delay Margin (sec) for K_P				
	0.1	0.3	0.5	0.7	0.9
0.05	5.648	1.597	0.571	0.378	0.245
0.10	2.580	1.416	0.625	0.365	0.230
0.15	1.497	1.171	0.577	0.343	0.229
0.20	1.029	0.970	0.541	0.334	0.221
0.25	0.713	0.808	0.504	0.314	0.210
0.30	0.531	0.671	0.465	0.303	0.205
0.35	0.388	0.575	0.420	0.287	0.195
0.40	0.291	0.481	0.312	0.222	0.182
0.45	0.209	0.409	0.354	0.256	0.180
0.50	0.134	0.349	0.323	0.211	0.172
0.55	0.097	0.297	0.227	0.220	0.162
0.60	0.052	0.247	0.239	0.211	0.150
0.65	0.018	0.206	0.234	0.196	0.147
0.70	-	0.164	0.211	0.182	0.136
0.75	-	0.133	0.183	0.167	0.1315
0.80	-	0.106	0.164	0.154	0.123
0.85	-	0.079	0.145	0.142	0.115
0.90	-	0.056	0.126	0.130	0.107
0.95	-	0.036	0.108	0.117	0.101
1.00	-	0.017	0.090	0.106	0.092
1.05	-	-	0.062	0.091	0.082
1.10	-	-	0.061	0.083	0.077
1.15	-	-	0.045	0.073	0.070
1.20	-	-	0.034	0.063	0.063
1.25	-	-	0.021	0.051	0.057
1.30	-	-	0.010	0.044	0.050
1.35	-	-	-	0.035	0.043
1.40	-	-	-	0.022	0.034
1.45	-	-	-	0.018	0.031

1.50	-	-	-	0.010	0.020
1.55	-	-	-	0.002	0.019
1.60	-	-	-	-	0.013
1.65	-	-	-	-	0.006
1.70	-	-	-	-	0.002
1.75	-	-	-	-	-

The sample plots of stable delay margin for different values of K_I for K_P=0.5 and K_P=0.7 are shown in Fig.6.

It is observed from the figure that there is a tendency for the delay margin to decrease gradually with the increase of K_I.

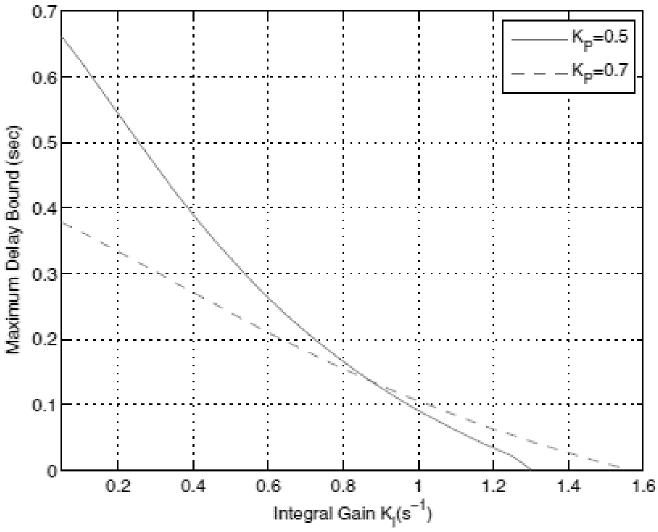

Fig.6. Variation of Maximum Time-Delay-with K_I.

The generator-excitation system is asymptotically stable for the communication delays lying in the region below the curves of Fig. 5 and Fig. 6 for given values of K_P and K_I.

For example, if K_P=0.7 and K_I=0.8, then the delay free excitation control system is asymptotically stable as observerd in Fig. 6.

However, in the presence of communication delay, according to the delay dependent stability criterion presented in Theorem, the excitation control system for the same value controller parameters is stable only up to τ=0.1553 seconds, and if communication delay increases beyond this value, the system becomes unstable.

Hence, the delay-dependent stability clearly brings out the impact of the communication delay on stability and performance of the system.

The characteristics given in Fig. 5 and Fig. 6 will serve as a guideline for fine tuning of the PI controller parameters at the implementation stage so as to obtain an optimal performance from the excitation control system in a real-time operating condition involving non-zero communication delays.

CONCLUSION

In this paper, a less conservative delay-dependent stability based LMI framework, based on Lyapunov-Krasovskii approach and Wirtinger inequality, was presented to ascertain the delay-dependent stability of a generator-excitation control system operated over a communication network that introduces time-delays in the feedback loop. Though time-varying in nature, result presented in this paper assumes that feedback loop delays are time-invariant. The effectiveness of the presented delay-dependent stability criterion was validated on a benchmark excitation control system with suitable simulation results. Thus, the delay-dependent stability criterion of the generator excitation control system by CAN bus is presented, which enables the determination of maximum delay margin in communication in the excitation control system, and overcomes the instability of the excitation control system resulting from the communication network delay. The main drawback is the difficulty of performing the stability analysis of the system in the case of time delay changes at each instant. Therefore, the important issue is how to facilitate stability analysis if the system has time-varying delay.

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