Stability A Networked Control System with Random Time Delays

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Abstract This paper investigates the effect of time delays on the stability of generator excitation control system. The time delays are due to the use of measurement devices Communication links for data transfer and controller processing time. The stability with respect to the time delay is theoretically analyzed and a formula to determine the maximum amount of time delay known as delay margin that the system can tolerate without losing its stability is presented. It is found that the excitation control system becomes unstable when the time delay crosses certain critical values, delay margins for stability. The main objective of this paper is to control the stability of generator excitation by PI controller, fuzzy and smith predictive controller, and to compare the results obtained by the two methods.

Keywords Electric power system, Generator excitation control, Time delay, Delay Margin, PI controller, fuzzy and smith predictive control.

I. INTRODUCTION

In electrical power systems, load frequency control (LFC) and excitation control system also known as automatic voltage regulator (AVR) equipment 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[1].This paper investigates the effect of the time delay on the stability of the generator excitation control system. Figure 1 shows the schematic block diagram of a typical excitation control system for a large synchronous generator. It consists of an exciter, a phasor measurement unit (PMU) a rectifier, a stabilizer, and a regulator [1].The exciter provides DC power to the synchronous generator's field winding constituting power stage of the excitation system. Regulator consists of a proportional-integral (PI) controller and an amplifier [2].The regulator processes and amplifies input control signals to a level and form appropriate for control of the exciter. The PI controller is used to improve the dynamic response as well as to reduce or eliminate the steady-state error. The amplifier may be magnetic amplifier, rotating amplifier, or modern power electronic amplifier. The PMU derives its input from the secondary sides of the three phases of the potential transformer (voltage transducer) and outputs the corresponding positive sequence voltage phasor. The rectifier rectifies the generator terminal voltage and filters it to a DC quantity. The stabilizer, which is an optional equipment, provides an additional input signal to the regulator to damp power system oscillations [2] . In order to clearly see effects of time delays on the oscillatory stability, stabilizer is not included in this study.

The operation of this system can be described as follows:

When an increase in the power load demand, especially in the reactive power load demand occurs, a drop in the generator terminal voltage ($|v_a|$) is observed. The voltage magnitude is sensed by the PMU through a potential transformer. The measured voltage is rectified and compared with a reference DC voltage. The PI controller produces an analog signal that controls the firing of a controlled rectifier shown as amplifier in Fig1.Thus, the regulator (PI controller and amplifier) controls the exciter field and increases the exciter terminal voltage. The generator field current is increased because of an increase in the exciter terminal voltage. Such an increase in the field current results in an increase in the generator electro-motor-force (emf).Thus, the reactive power generation is increased to a new equilibrium point, raising the generator terminal voltage to the desired value. Time delays have become an important issue in power system control and dynamic analysis since the use of phasor measurement unit (PMUs) and open and distribute communication networks for transferring measured signals and data to the controller have introduced significant amount of time delays. The PMUs are units that measure dynamic data of power systems, such as voltage, current, angle, and frequency using the Discrete Fourier Transform (DFT)[3].In power system control, various communication links used for data transfer include both wired options such as telephone lines, fiber-optic cables, and power lines, and wireless options such as satellites [4] and internet [5] . The use of PMUs introduces the measurement delays that consist of voltage transducer delay and processing delay. The processing delay is the amount of time required in converting transducer data into phasor information with the help of DFT. In power system control, the total measurement delay is reported to be in the order of the milli seconds. Depending on the communication link used, the total communication delay is considered to be in the range of 100-700ms.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 power system control. This delay can typically be in the range of 0.5-0.1s[6]It is obvious that when voltage signal is measured from remote location and transferred to the local controller, the communication delay will increase [7] Another processing delay in the order of milliseconds is observed when a digital PI controller is used in the regulator located in the feed-forward section of the AVR The inevitable time delays in power system 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. In the design of a controller, time delays must be taken into account and analytical tools should be developed to study the complicated dynamic behaviour of delayed power systems. Especially, such tools should estimate the maximum amount of time delay that the system could tolerate without losing its stability. Such knowledge on the delay margin (upper bound in the time delay) could also be helpful in the controller design for cases where uncertainty in the delay is unavoidable. Until now, many researchers have mainly focused on the destabilizing effect of the time delay on the load frequency control (also known as automatic generation control) [7] and power system stabilizer design [8] . To best of our knowledge, methods for analyzing time delays in the generator excitation control systems do not exist in the literature. Therefore, there is a need to develop a practical method that will allow us to compute delay margin of AVR system with processing and communication delays quantitatively. This paper presents a frequency-domain approach to determine the conditions of delay-independent and delay-dependent asymptotic stability [9] of the excitation control system and a practical method to determine delay margin of the delay-dependent case. Similarly by using the rekasius substation method was proposed in the literature to investigate the stability of other time-delayed systems. The comparison of the proposed method with the other

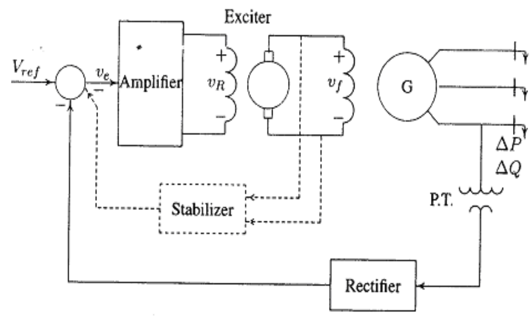

Figure 1 : A typical arrangement of a simple AVR.

methods utilizing rekasius substitution method given in[10]indicates that this approach is effective of the time delay system. In this work, an analytical formula is derived to compute delay margin. The theoretical results on the delay margin are verified by using pi, fuzzy and smith predictive controllers in time domain simulation capabilities of Matlab/Simulink. It must be mentioned here that the proposed method could be easily applied to the stability estimation and delay margin computation of other linear time-invariant (LTI) time delayed systems.

II. GENERATOR EXCITATION CONTROL SYSTEM MODEL WITH TIME DELAYS.

For load frequency control and excitation control system linear or linearized models are commonly used to analyze the system dynamics and to design a controller. Figure2 shows the block diagram of a generator excitation control system with time delays. Each component of the amplifier, exciter, sensor, generator are modified by the first order transfer function .The transfer function of each component is gives as follows

$$G_A(S) = \frac{V_R(S)}{V_e(s)} = \frac{K_A}{1+K_A S}$$

$$G_E(S) = \frac{V_F(S)}{V_R(S)} = \frac{K_E}{1+T_E S}$$

$$G_R(S) = \frac{V_S(S)}{V_t(s)} = \frac{K_R}{1+T_R S}$$

$$G_G(S) = \frac{V_t(s)}{V_F(S)} = \frac{K_G}{1+T_G S} \qquad \text{.............(1)}$$

where, KA, KE, KG, and KR are the gains of amplifier, exciter, generator, and sensor, respectively, and TA,TE, TG and TR are the corresponding time constants.

The transfer function of the PI controller is described as

$$G_C(S) = K_P + \frac{K_I}{S} \qquad \text{..........(2)}$$

where KP and KI are the proportional and integral gains, respectively. The proportional term affects the rate of voltage rise after a step change. Combined effect of the

PI controller will shape the response of the generator excitation system to reach the desired performance.

As illustrated in Fig. 2 using exponential terms, the total of measurement and communication delays Γ_1 and Γ_2 is placed in the feedback part while the processing delay Γ_2 is placed in the feed-forward part of the excitation control system. The characteristic equation of the excitation system can be obtained easily from

$$\Delta(s,\Gamma)=1+G_C(S)G_A(S)G_E(S)G_G(S)G_R(S)e^{-s(\Gamma_1+\Gamma_2)}=0 \quad (3)$$

and it can be written as

$$\Delta(s,\Gamma)=P(s)+Q(s)e^{-s\Gamma}=0 \text{ ....(4)}$$

Where $\Gamma=(\Gamma_1+\Gamma_2)$ and P(s),Q(s) are polynomials in s with real coefficients given below.

$$P(s)=T_5S^5+T_4S^4+T_3S^3+T_2S^2+S$$

$$Q(s)=(K_PS+K_I)K_AK_EK_GK_R \text{ ....(5)}$$

In order to investigate the stability of the excitation control system, we need to study the location of the roots of the characteristic equation of (4) . In the following section, theoretical stability analysis that results in a formula to compute delay margin for a stable operation is presented

III. STABILITY ANALYSIS.

The main objective of this is to study the stability of the time delay and to determine conditions on the delay for any given set of system parameters that will guarantee the stability of the system. As with the delay-free system (i.e., Γ = 0) , the stability of excitation system depends on the locations of the roots of system characteristic equation defined by (4) . It is obvious that the roots of (4) are functions of the time delay Γ. As Γ changes, locations of the roots may change. For the system to be asymptotically stable, all the roots of the characteristic equation of (4) must lie in the left half of the complex plane.

Depending on system parameters, there are two different possible types of asymptotic stability situations due to the time delay Γ.

Delay-independent stability :The characteristic equation of (4) is said to be delay independent stability.

Delay dependent stability: The characteristic equation of (4) is said to Delay-dependent stability be if the condition we present a practical approach that gives a criterion for evaluating the delay dependency of stability and an analytical formula to compute the delay margin for the delay-dependent case.

- Solution method

A necessary and sufficient condition for the system to be asymptotically stable is that all the roots of the characteristic equation of (4) lie in the left half of the complex plane. In the single delay case, the problem is to find values of system for which the characteristic equation of (4) has roots (if any) on the imaginary axis of the plane Assume for simplicity that

Δ (s, 0) = 0 has all its roots in the left half-plane. Hence, looking for roots on the imaginary axis reduces to finding values of τ for which Δ(s, τ) = 0 and Δ(−s, τ) = 0 have a common root. That is

$$P(s)+Q(s)e^{-s\Gamma}=0$$

$$P(-s)+Q(-s)e^{s\Gamma}=0 \text{ ....(6)}$$

By eliminating the exponential terms in the above equations we get the following polynomial

$$P(s)P(-s)-Q(s)Q(-s)=0 \text{ ....(7)}$$

If we replace s by jw in (7) then we have the following polynomial w^2.

$$W(\omega^2)=P(j\omega)P(-j\omega)-Q(j\omega)Q(-j\omega)=0 \text{ ..(8)}$$

Substituting P(s) and Q(s) in the given 5 into we obtain.

$$W(\omega^2)=P_{10}\omega^{10}+P_8\omega^8+P_6\omega 6+P_4\omega^4+P_2\omega^2+P_0=0 \text{ ...(9)}$$

where the coefficients p0, p2, p4, p6, p8, andp10 are real valued and are given in Appendix A

If there exist the positive roots of the polynomial (9) with respect to ω2 , then the system is delay-dependent stable. Once the relevant positive roots of (9) the corresponding Γ value of can be obtained as follows.

$$\Delta(j\omega_k,\Gamma)=P(j\omega_k)+Q(j\omega_k)e^{-j\omega_k\Gamma}=0$$

$$e^{-j\omega_k\Gamma}=\cos(\omega_k\Gamma)-j\sin(j\omega_k\Gamma)=-\frac{P(j\omega_k)}{Q(j\omega_k)} \text{ ......(10)}$$

from (10) we can determine an analytical formula for the upper bound of the time delay Γ^* as follows.

$$\Gamma^*_{k,r}=\frac{\theta}{\omega_k}+\frac{2r\Pi}{\omega_k};r=0,1,2,3\ldots\ldots\infty \text{.....(11)}$$

Where $\theta=\tan^{-}\left(\frac{\mathrm{Im}\left\{\frac{P(j\omega_k)}{Q(j\omega_k)}\right\}}{\mathrm{Re}\left\{-\frac{P(j\omega_k)}{Q(j\omega_k)}\right\}}\right)$

An analytical formula for the angle θ and for the upper bound on the delay size for the exciter control system can easily be obtained by substituting P(s) and Q(s) polynomials given in (5) into (11).

$$\Gamma^*_{k,r} = \frac{\theta}{\omega_k} + \frac{2r\prod}{\omega_k}; r = 0,1,2,3......$$

$$\theta = \tan^{-}\left(\frac{q_5\omega_k^5 + q_3\omega_k^3 + q_1\omega_k}{q_6\omega_k^6 + q_4\omega_k^4 + q_2\omega_k^2}\right) ...(12)$$

where the coefficients q1, q2, q3, q4, q5, and q6 are real-value and are given in Appendix A . Please note that π must be added to or subtracted from the angle θ when $q_6\omega_k^6 + q_4\omega_k^4 + q_2\omega_k^2 < 0$ to correct delay margin results in $\Gamma^*_{k,r}$ Please note that the polynomial of (12) exhibits only a finite number of positive real roots $\omega_k^2; k = 1,2,3......q$ where q is the number of positive real roots of (12) . This finite number q is influenced not only by the system order n but also by the coefficients of the polynomial P(s), Q(s). $\omega_k^2; k = 1,2,3......$ we can get infinitely many $\Gamma^*_{k,r}$ values. According to the definition of delay margin, the minimum of $\Gamma^*_{k,1}, k = 1,2,3.......q$ is the system delay margin.

- Rekasius substitution

The critical procedure is an exact substitution in equation (13) This exact substitution creates a new characteristic equation

$$CE = (s,\Gamma) = \sum_{k=0}^{p} a_k(s)e^{-k\Gamma s} = 0 ...(13)$$

$$e^{-\Gamma s} = \frac{1-TS}{1+TS} \text{ where s=ωj.} \quad ...(14)$$

Where $\Gamma = \frac{2}{\omega}\left[\tan^{-1}(\omega T) \pm l\prod\right]$,l=0,1,2….

This exact substitution creates the new characteristic equation as follows

$$CE = (s,\Gamma) = \sum_{k=0}^{p} a_k(s)\left(\frac{1-TS}{1+TS}\right)^K = 0 \quad ..(15)$$

multiplying the above equation with $(1+TS)^p$ we obtain

$$\sum_{k=0}^{p} a_k(S)(1+TS)^{p-k}(1-TS)^K = 0 \quad ....(16)$$

Considering that ak(s) are ordinary polynomials, equation (15) is nothing other than a polynomial in s with parameterized coefficients in (T). Since the system in equation (1) is retarded type, the highest degree term of s is n and it is in a0 (s) . Equation (15), therefore, is a polynomial of s in degree n + p. which cause imaginary roots of s =ω i . This can be achieved by forming the Routh's array of the equation (32), and setting the only term in the s1 row to 0.nce these roots are determined the corresponding crossing frequencies (s=jw) can be found using the auxiliary equation, which is formed by the s2 row of the Routh array They must agree in sign for those T values to yield imaginary roots. Final results are exhaustive in detecting all the imaginary characteristic roots we set out to solve. In the case of degenerate imaginary roots at the origin s=jw with w =0 one needs to check in addition, the constant term in equation (15) with no s term; if

$$\sum_{k=0}^{p} a_k(0) = 0.$$

IV. FUZZY SYSTEM

The fuzzy interface system Fuzzy system basically consists of a formulation of the mapping from a given input set to an output set using Fuzzy logic. The mapping process provides the basis from which the interference or conclusion can be made.

Fuzzy interface process consists of following steps

Step 1:Fuzzification of input variables.

Step 2: Application of Fuzzy operator.(AND, OR, NOT) In the IF (antecedent) part of the rule.

Step 3: Implication from the antecedent to the consequent (Then part of the rule).

Step 4: Aggregation of the consequents across the rules.

Step 5: Defuzzification.

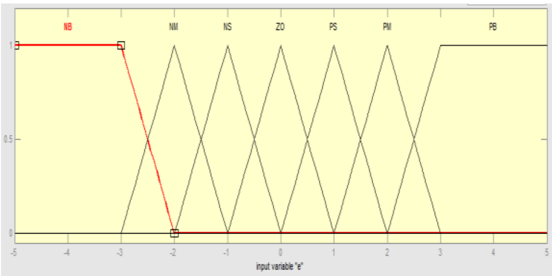

Fig 3 input (e) error

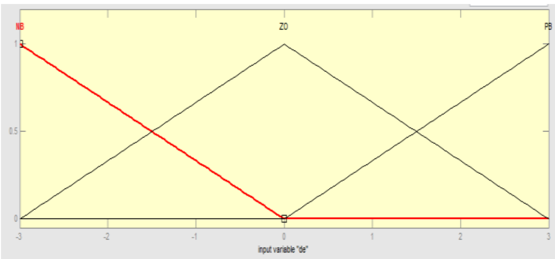

Fig 4 input(de) change in error

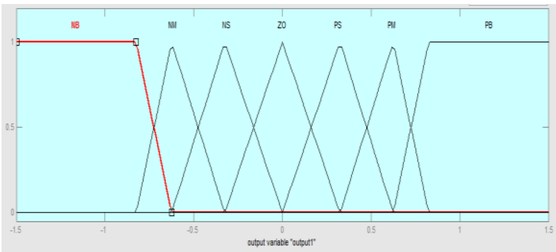

Fig 5. output

- Smith predictor

If a time delay were introduced into an optimally tuned system, the gain would have to be reduced to maintain stability. The Smith predictor avoids this reduction of gain and consequent poorer performance.

The following development of the Smith predictor was developed by the block diagram for conventional control of a time-delay system. For simplicity, I will use the shorthand notation of Marshall **[3]:** R represents the system input, **R(s);** C represents the controller, **C(s);** L represents potential load disturbances, L(s); G, represents plant dynamics, G,(s); T, represents the plant time delay, T,(s); and Y, represents the plant output, **Y,(s).** For a simple first-order plant with a pure time delay.**G,** represents the model of the plant dynamics, T, represents the model of the plant time delay, and E represents the error between the output of the model and the output of the plant. The effects of the time delay have been removed from the denominator of the transfer function, and the system performance has been improved. However, it tracks input variations with a time delay.

V. THEORETICAL AND SIMULATION RESULTS

Theoretical delay margin results are verified by using Matlab/Simulink. The gain and time constants of the exciter control system used in the analysis are as follows [1] KA = 5, KE = KG = KR = 1.0 and TA = 0.1s, TE =0.4s, TG = 1.0s, TR = 0.05s.Delay-free system $\Gamma = 0$ should be stable in order to be able to investigate and show how increasing time delay makes the exciter control system unstable. The range of maximum PI controller gains such that the delay exciter control system will be at least marginally stable could be easily determined by applying the Routh-Hurwitz stability criterion to the characteristic equation of (4) or by using the time-domain simulation. Matlab/Simulink is used to verify the theoretical results on the delay margin. Simulink model of the exciter system presented in Fig. 2 Note that transfer function blocks of Simulink model for the excitation system is given in fig 6. And are used to model the amplfier, exciter, generator and sensor. The measurement communication delay in the feedback path, processing delay in the feed-forward path and fuzzy controller and smith predictive controllers are implemented for the transportation block and smith predictive block of Simulink, respectively. For any given delay and system parameters, we can obtain the system response to a step input. The box Vt and scope are to obtain the output voltage data and waveforms upon a step input. The theoretical results on the delay margin will be verified using time-domain simulations. For illustration purpose ,we choose PI controller gains K P = 0.7 , K I = 0.8 s−1. From Table 1 for these gains, the delay margin is Γ^* =0.1554 Simulation result for this delay value is shown in Fig 7 It is clear that sustained oscillations occur verifying ,it is expected that the exciter system will be stable.fig 8.shows such a simulation result for Γ = 0.14s Similarly, when the time delay is larger than the delay margin, the system will have growing oscillations indicating an unstable operation.

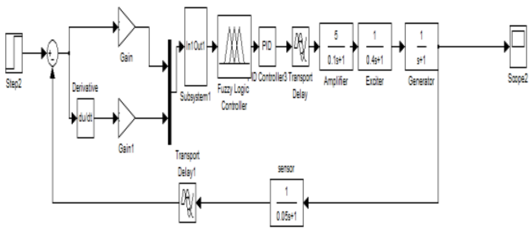

Fig 6 simulink model for generator excitation system with smith predictive controller.

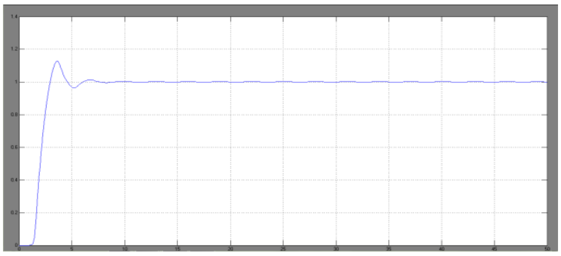

Fig 7 for stable operation K_P=0.7,K_I=0.8 s^{-1} and Γ =0.05

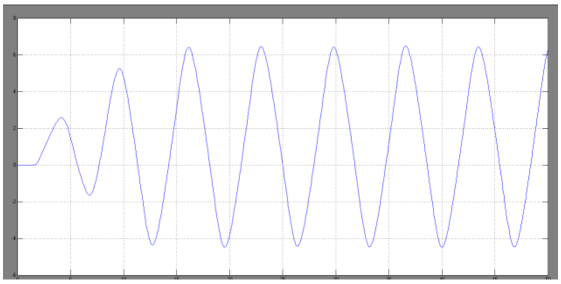

Fig 8 for unstable operation K_P=0.7,K_I=0.8 s^{-1} and Γ =1

VI. CONCLUSIONS

In this paper, the stability of the generator excitation control system is analyzed in the presence of unavoidable delays observed both in the feedback and feed-forward parts of the system. A methodology for determining the conditions for delay-dependent and delay-independent stability and for computing delay margins in the delay-dependent case are presented. The computed delay margins are verified using time-domain simulations of Matlab/Simulink. It must be mentioned here that the proposed method and by using rekasius substitution method it could be easily applied to the stability estimation and delay margin computation of other linear time-invariant(LTI)time-delayed systems. When the excitation system is compared with the PI controller the fuzzy and smith predictor controller are becomes more stable in time delay system the generator excitation system .In the future, a stabilizer will be added to the exciter system and its effects on the delay margin will be investigated, Moreover, the presented method will be applied to the delayed load-frequency control of power systems.

Appendix A

The coefficients of the polynomial P(s) given in (5)

$$T_5 = T_A T_E T_G T_R$$

$$T_4 = T_A T_E T_R + T_A T_E T_G + T_G T_E T_R + T_A T_G T_R$$

$$T_3 = T_A T_E + T_G T_E + T_G T_R + T_R T_E + T_A T_R + T_A T_G$$

$$T_2 = T_A + T_E + T_G + T_R$$

The coefficients of the polynomial $W(w^2)$ given in (9)

$$P_{1O} = T_5^2$$

$$P_8 = T_4^2 - 2T_5 T_3$$

$$P_6 = T_3^2 + 2T_5 - 2T_5 T_2$$

$$P_4 = T_2^2 - 2T_3$$

$$P_2 = 1 - \left(K_A K_E K_G K_R\right)^2 K_P^2$$

$$P_0 = -\left(K_A K_E K_G K_R\right) K_I^2$$

The coefficients of the analytical formula given in (13)

$$q_1 = KK_I$$

$$q_2 = K\left(K_I T_2 - K_P\right)$$

$$q_3 = K\left(K_P T_2 - K_I T_3\right)$$

$$q_4 = K\left(K_P T_3 - K_I T_4\right)$$

$$q_5 = K\left(K_I T_5 - K_P T_4\right)$$

$$K = K_A K_E K_G K_R$$

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