Stability of a Two-Area Automatic Generation Control System with Communication Delays

Saffet Ayasun[1] and Chika O. Nwankpa[2]

[1]Department of Electrical and Electronics Engineering, Niğde University, 51100 Niğde TURKEY
sayasun@nigde.edu.tr
[2]Department of Electrical and Electronics Engineering, Drexel University, Philadelphia, PA 19104 USA
chika@nwankpa.ece.drexel.edu

Abstract

This paper investigates the effect of time delays on the stability of a two-area automatic generation control (AGC) system. The time delays are due to the use of measurement devices and communication links for sending and receiving control signals. The maximum amount of time delay known as the delay margin that the system can tolerate without becoming unstable is determined using Matlab/Simulink. The effect of integral controller gain on delay margin is analyzed.

1. Introduction

With use of open communication infrastructure and phasor measurement units (PMU) in the wide-area measurement/monitoring systems (WAMS), time delays have become inevitable, and raise concerns about the system dynamic response [1, 2]. The total time delay consisting of measurement and communication delays in power systems has a destabilizing impact, reduces the effectiveness of control system damping and leads to unacceptable performance such as loss of synchronism and instability [3-6]. In this paper, we focus on the effects of time delays on the stability performance of automatic generation control system (AGC). In an interconnected power system consisting of several pools, the primary role of the AGC is to divide the loads among system, stations, and generators to achieve maximum economy and correctly control the scheduled interchanges of tie-line power flow while maintaining a reasonably uniform frequency [7].

Traditionally, dedicated communication links were used to send AGC control signals. For this reason, in stability analysis it was reasonable to neglect the time delays associated with the communication network. However, the communications delays significantly increase when an open and distributed communication network is used to send AGC control signals [3, 4]. It was reported that communication delays in AGC systems can be in the range of 5-15 sec [6].

The size of communication delays in WAMS mainly depends on the physical media of communication (such as fiber-optic-cables, digital microwave links, power line, telephone lines and satellite links [1]) as well as several other factors including the phasor package size, transmission protocol employed and communication network load (congested or idle). As a result, these delays may fluctuate randomly in a certain range. Therefore, it is essential to estimate the maximum amount of time delay known as the delay margin that the system could tolerate without becoming unstable. Such knowledge on the delay margin (upper bound in the time delay) will be helpful in the controller design for cases where uncertainty in the delay is unavoidable.

Delay margins of the AGC system for a certain set of parameters could be determined either by using theoretical methods reported in the literature or by a time-domain simulation approach. The common starting point of theoretical methods is the determination of all the imaginary roots of the characteristic equation. The existing procedures can be classified into the following five distinguishable approaches: i) Schur-Cohn (Hermite matrix formation) [8-10]; ii) Elimination of transcendental terms in the characteristic equation [11]; iii) Matrix pencil, Kronecker sum method [8-10, 12]; iv) Kronecker multiplication and elementary transformation [13]; v) Rekasius substitution [14-16]. These methods demand numerical procedures of different complexity and they may result in different precisions in computing imaginary roots. A detailed comparison of these methods, demonstrating their strengths and weakness can be found in [17]. Among these methods, only two of them have been recently applied to the stability analysis of time-delayed power systems. The method reported in [9] was effectively used to estimate the delay margin for automatic generation control systems with commensurate time delays [6]. The exact method based on Rekasius substitution presented in [15] is applied into small-signal stability analysis of power system to compute delay margins [18].

In this paper, a time-domain simulation approach is implemented by using MATLAB/SUMULINK [19] to determine the delay margin for several values of integral controller gain. The results indicate how the delay margin decreases as the integral control gain increases, an indication of a less stable operation. The main contribution of this paper is the qualitative analysis of the relationship between the delay margin and integral controller gain, which has not been reported in the literature.

2. Small-Signal Stability of Time-Delayed Power System

When a time delay is observed in the system, power system dynamics should be described by the following time-delayed differential-algebraic equation (DAE) model [18]:

$$\begin{cases} \dot{x} = f(x, y, x_\tau, y_\tau, \beta) \\ 0 = g(x, y, \beta) \\ 0 = g(x_\tau, y_\tau, \beta) \end{cases} \tag{1}$$

where $x \in \Re^n$ and $x_\tau = x(t-\tau) \in \Re^n$ are the vectors of delay-free and time-delayed state variables, respectively such as rotor angles and control states of exciter and speed governor; $y \in \Re^m$ and $y_\tau = y(t-\tau) \in \Re^m$ are the vectors of delay-free and time-delayed algebraic variables, respectively such as voltage magnitude and phase angles at the load buses; $\tau > 0$ is the constant time delay observed in the system. It must be noted that all the time delays observed are assumed to be constant and equal. $\beta \in \Re^k$ is the vector of parameters such as real/reactive power demand at the buses, transmission line parameters, and control set points and gains. The dynamics of generators, control devices (exciter, speed governor, stabilizer) and load dynamics together define the set of differential equations. The algebraic equations are the power flow equations representing real and reactive power balances at the load buses.

The small-signal stability is the ability of the power system to maintain synchronism under small disturbances that occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations around an equilibrium point to be permissible for the purpose of stability analysis [7]. By linearizing (1) at an equilibrium point (x_0, y_0), we can easily obtain the following incremental DAE:

$$\begin{aligned} \Delta\dot{x} &= \left[A_0(\beta)\right]\Delta x + \left[A_\tau(\beta)\right]\Delta x_\tau \\ &\quad + \left[B_0(\beta)\right]\Delta y + \left[B_\tau(\beta)\right]\Delta y_\tau \\ 0 &= \left[C_0(\beta)\right]\Delta x + \left[D_0(\beta)\right]\Delta y \\ 0 &= \left[C_\tau(\beta)\right]\Delta x_\tau + \left[D_\tau(\beta)\right]\Delta y_\tau \end{aligned} \tag{2}$$

where

$$\begin{aligned} &A_0(\beta) = \left.\frac{\partial f}{\partial x}\right|_\beta; \; B_0(\beta) = \left.\frac{\partial f}{\partial y}\right|_\beta; \; C_0(\beta) = \left.\frac{\partial g}{\partial x}\right|_\beta; \\ &D_0(\beta) = \left.\frac{\partial g}{\partial y}\right|_\beta; A_\tau(\beta) = \left.\frac{\partial f}{\partial x_\tau}\right|_\beta; \; B_\tau(\beta) = \left.\frac{\partial f}{\partial y_\tau}\right|_\beta; \\ &C_\tau(\beta) = \left.\frac{\partial g}{\partial x_\tau}\right|_\beta; \; D_\tau(\beta) = \left.\frac{\partial g}{\partial y_\tau}\right|_\beta \end{aligned} \tag{3}$$

are the Jacobian matrices with respect to the state and algebraic variables and the time-delayed state and algebraic variables evaluated at the equilibrium point (x_0, y_0). When the algebraic Jacobian matrices D_0, D_τ are non-singular, the incremental DAE of (2) could be reduced to a set of incremental ordinary differential equations (ODEs), and local dynamics in the neighborhood of the equilibrium point could be investigated by the time-delayed ODEs of the form:

$$\Delta\dot{x}(t) = \left[\tilde{A}_0(\beta)\right]\Delta x(t) + \left[\tilde{A}_\tau(\beta)\right]\Delta x_\tau(t-\tau) \tag{4}$$

where

$$\left[\tilde{A}_i(\beta)\right] = \left[A_i(\beta)\right] - \left[B_i(\beta)\right]\left[D_i(\beta)\right]^{-1}\left[C_i(\beta)\right]; \; i = 0, \tau$$

The stability of the linear time-delayed system given in (4) is determined by the location of system eigenvalues that can be obtained from the following characteristic equation:

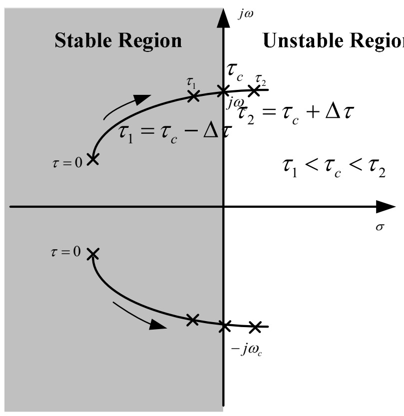

Fig. 1. Illustration of the movement of the characteristic roots with respect to the time delay

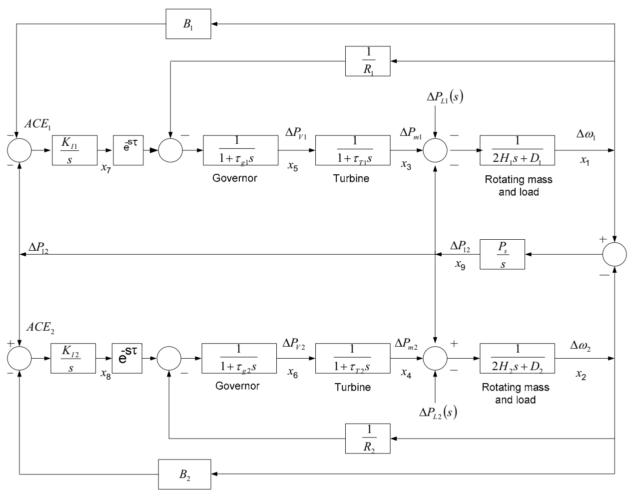

Fig. 2. Block diagram of AGC with time delay for a two-area system

$$\Delta(s,\tau) = det\left[sI - \tilde{A}_0(\beta) - \tilde{A}_\tau(\beta)e^{-s\tau}\right] = P(s) + Q(s)e^{-s\tau} = 0 \tag{5}$$

where $P(s), Q(s)$ are polynomials in s with real coefficients determined by the elements of $\left[\tilde{A}_0\right]$ and $\left[\tilde{A}_\tau\right]$ matrices. It is obvious that the roots of (5) are a function of the time delay τ. Let's denote these roots by $s^\tau = \left[s_1^\tau, s_2^\tau, \ldots, s_n^\tau\right]$. Similar to the delay-free system ($\tau = 0$), if the following condition is held, then the system is said to be small-signal stable.

$$max\left(real\left(s_i^\tau\right)\right) < 0 \text{ for } \forall s_i^\tau \in s^\tau \text{ or } \forall s_i^\tau \in \mathrm{C}^- \tag{6}$$

In other words, if all the roots are in the negative half part of the complex plane, the system is small-signal stable.

Depending on system parameters, there are two different possible types of asymptotic stability situations due to the time delay τ [8, 11]:

i) *Delay-independent stability*: The characteristic equation of (5) is said to be *delay-independent stable* if the stability condition of (6) holds for all positive and finite values of the delay, $\tau \in [0,\infty)$.

ii) *Delay-dependent stability*: The characteristic equation of (5) is said to be *delay-dependent stable* if the condition of (6) holds for some values of delays belonging in the delay interval, $\tau \in [0,\tau_c)$, and is violated for other values of delay $\tau \geq \tau_c$.

In the delay-dependent case, the roots of the characteristic equations move as the time delay τ increases starting from $\tau = 0$. Fig. 1 illustrates the movement of the roots. Note that the delay–free system ($\tau = 0$) is assumed to be stable. This is a realistic assumption since for the practical values of system parameters the AGC system is stable when the total delay is neglected. Observe that as the time delay τ is increased, a pair of complex eigenvalues moves in the left half of the complex plane. For a finite value of $\tau > 0$, they cross the imaginary axis and pass to the right half plane. The time delay value τ_c at which the characteristic equation has purely imaginary eigenvalues is the upper bound on the delay size or the delay margin for which the system will be stable for any given delay less or equal to this bound, $\tau \leq \tau_c$. In order to characterize the stability property of (5) completely, we need to determine whether the system for any given set of parameters is delay-independent stable or not, and if not, to determine the delay margin τ_c for a wide range of system parameters.

3. AGC System Model with Time Delay

The block diagram of a simple AGC for a two-area system is shown in Fig. 2. Note that the two areas are interconnected by a lossless line. During the normal operation certain amount of real power is transferred over this line. The change in the power flowing is denoted by ΔP_{12} . The tie-line power flow begins whenever a load increment or decrement occurs in one of the areas. The main goals of this system are: i) Keep frequency approximately at the nominal value, ii) Maintain tie-line power flow at about the scheduled value, iii) Make sure that each area should absorb its own load changes [7]. Note that in each control area the AGC regulator is designed to respond to Area Control Error (ACE), and integral controller is used to eliminate ACE used as actuating signals to activate changes the reference power set points. The ACE is composed of a linear combination of tie-line power flow deviation and the frequency deviation weighted by a bias factor, which is called tie-line bias control (TBC).

$$\begin{aligned} ACE_1 &= \Delta P_{12} + B_1 \Delta\omega_1 \\ ACE_2 &= \Delta P_{21} + B_2 \Delta\omega_2 \end{aligned} \tag{7}$$

Note that a time delay block is added to each control area at the output of the integral controller. In an open communication system, delays can arise during: i) transmission of ACE signals from the control center to the individual units and ii) from a telemetry delay when Remote Terminal Units (RTUs) send the remote signals to the control center. In the model, all such delays are aggregated into a single delay from the control center [6].

The AGC system shown in Fig. 2 could be easily modeled as a time-delayed linear time-invariant (TDLTI) system. The state-space equation model is given as

$$\dot{x}(t) = \tilde{A}_0 x(t) + \tilde{A}_\tau x(t-\tau) + B_1 u_1(t) + B_2 u_2(t) \tag{8}$$

where the state-space variables are defined as: $x_1 = \Delta\omega_1, x_2 = \Delta\omega_2, x_3 = \Delta P_{\mathrm{m1}}, x_4 = \Delta P_{\mathrm{m2}}, x_5 = \Delta P_{\mathrm{V1}}, x_6 = \Delta P_{\mathrm{V2}}$ and x_7 = controller output of area 1, x_8 = controller output of area 2, and $x_9 = \Delta P_{12}, u_1 = \Delta P_{\mathrm{L1}}, u_2 = \Delta P_{\mathrm{L2}}$. The system matrices are given in the Appendix.

4. Simulation Results

Simulink model of time-delayed AGC system is realized to determine delay margins for a wide range of integral controller gains for which the delay-free system is stable. The system parameters used in simulations can be found in Appendix. In order to clearly see the destabilizing effects of the delay on the AGC system, the delay-free system must be stable. For this reason, the integral controller gains selected should result in a stable operation. The stability range for the integral controller gain K_{I} is found to be $K_{\mathrm{I}} = K_{\mathrm{I}_1} = K_{\mathrm{I}_2} \leq 0.74$ using the time-domain simulation capabilities of Simulink program. Figure 3 shows the frequency response of the delay-free system for $K_{\mathrm{I}} = 0.74$. The sustained oscillations clearly indicate a marginally stable operation. Thus, the upper limit for the integral controller gain is $K_{\mathrm{I}} = 0.74$. For $K_{\mathrm{I}} > 0.74$, the delay-free system will be unstable as shown in Fig. 4 and it will stable for $K_{\mathrm{I}} < 0.74$ as presented in Fig. 5.

For a $\Delta P_{\mathrm{L1}} = 0.2$ pu load increase in area 1, simulations are performed and delay margins are obtained for several different values of the integral controller gain by investigating the time-domain response of AGC system. Delay margins are the delay values at which sustained (undamped) oscillations are observed in the system response. Figure 6 shows the variation of the delay margin with respect to the integral controller gain. It is clear that the delay margin significantly decreases when the integral controller gain is increased, which makes the AGC system less stable. To illustrate how the stability of the AGC system changes with respect to the time delay, we choose integral controller gains of $K_{\mathrm{I}} = 0.25$ for which the delay free system is stable and investigate the frequency deviation of the AGC system.

For $K_{\mathrm{I}} = 0.25$, the delay margin is found to be $\tau_c = 5.6725$ s . The frequency deviations of each area for this delay value are shown in Fig. 7. It is clear that sustained oscillations in system angular frequencies are occurred verifying the marginal stability. When the time delay is less than the delay margin ($\tau = 5.45$ s $< \tau_c$), the oscillations are decaying and the AGC system is stable, as shown in Fig. 8. When the time delay is larger than the delay margin ($\tau = 6.2$ s $> \tau_c$), the system has growing oscillations indicating an unstable operation, as illustrated in Fig. 9.

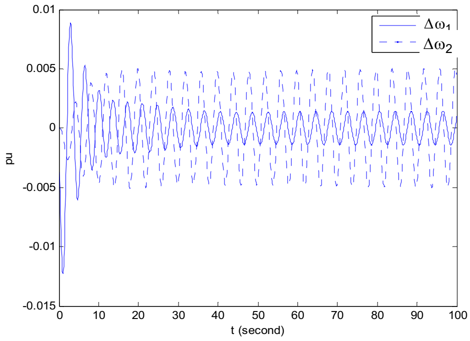

Fig. 3. Frequency deviation of the delay-free system for $K_I = 0.74$: Marginally stable operation

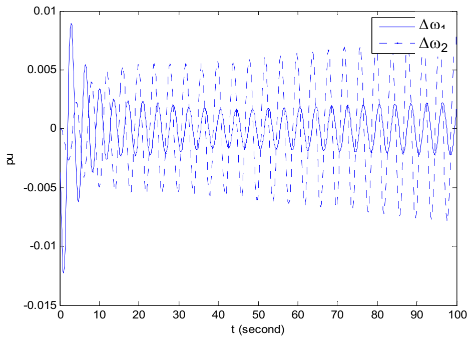

Fig. 4. Frequency deviation of the delay-free system for $K_I = 0.75$: Unstable operation

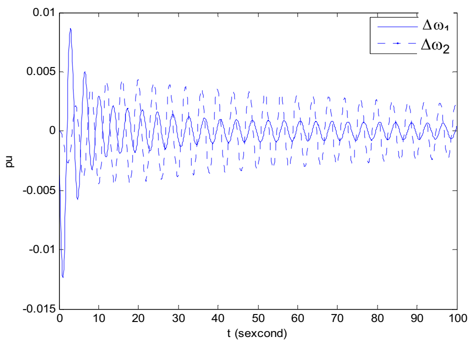

Fig. 5. Frequency deviation of the delay-free system for $K_I = 0.73$: Stable operation

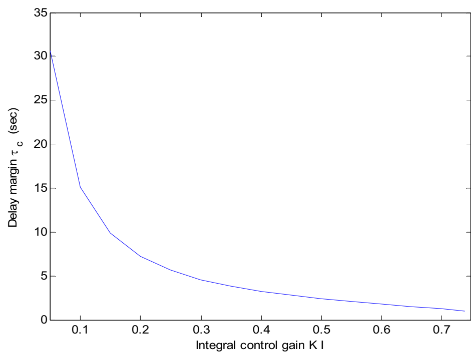

Fig. 6. Variation of the delay margin with respect to the integral controller gain

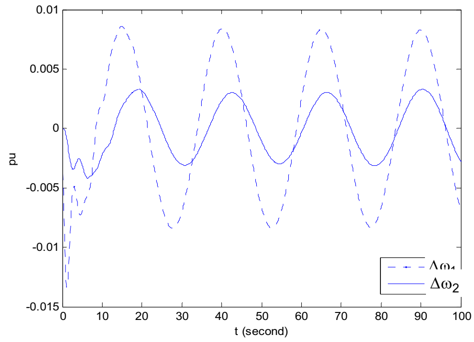

Fig. 7. Frequency deviation for $K_I = 0.25$ and $\tau_c = 5.6725$ s: Marginally stable operation

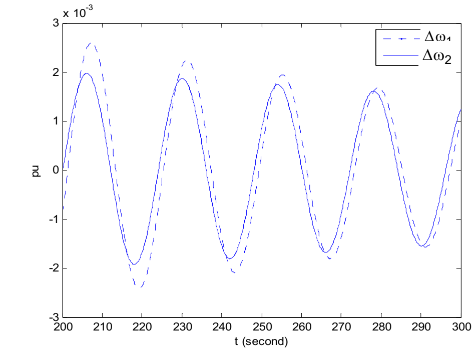

Fig. 8. Frequency deviation for $K_I = 0.25$ and $\tau = 5.45$ s: Stable operation

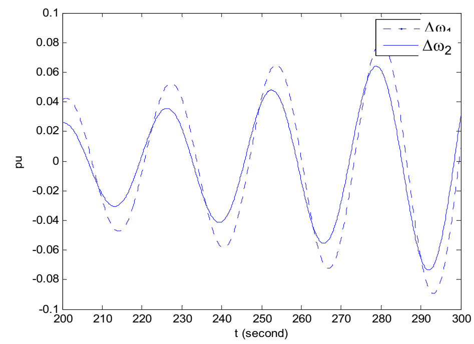

Fig. 9. Frequency deviation for $K_I = 0.25$ and $\tau = 6.2$ s: Stable operation

5. Conclusions

This paper studies the destabilizing effects of communication delays on a two-area AGC system. Using a simulation approach, delay margins for a wide range of controller gains have been determined. It has been shown that the delay margin decreases significantly as the controller gain changes in a narrow range, making the AGC system less stable. Simulation results clearly indicate that communications delays must be taken into account in the controller design and gain selection.

In the future, two main assumptions of the paper on constant time delay and bifurcation type (Hopf bifurcation) will be relaxed, the time-dependency and randomness of communication delays will be considered. Moreover, delay margins will be computed using two different theoretical methods [11, 15] and results will be verified by the time-domain simulations using MATLAB/Simulink.

6. Appendix

The system matrices given in Eq. (8) are defined as follows:

$$\tilde{A}_0 = \begin{bmatrix} -\frac{D_1}{2H_1} & 0 & \frac{1}{2H_1} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2H_1} \\ 0 & -\frac{D_2}{2H_2} & 0 & \frac{1}{2H_2} & 0 & 0 & 0 & 0 & \frac{1}{2H_2} \\ 0 & 0 & -\frac{1}{\tau_{T1}} & 0 & \frac{1}{\tau_{T1}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau_{T2}} & 0 & \frac{1}{\tau_{T2}} & 0 & 0 & 0 \\ -\frac{1}{R_1\tau_{g1}} & 0 & 0 & 0 & -\frac{1}{\tau_{g1}} & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{R_2\tau_{g2}} & 0 & 0 & 0 & -\frac{1}{\tau_{g2}} & 0 & 0 & 0 \\ -K_{I_1}B_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{I_1} \\ 0 & -K_{I_2}B_2 & 0 & 0 & 0 & 0 & 0 & 0 & K_{I_2} \\ P_s & -P_s & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\tilde{A}_\tau = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\tau_{g1}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\tau_{g2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B_1 = \begin{bmatrix} -\frac{1}{2H_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$B_2 = \begin{bmatrix} 0 & -\frac{1}{2H_2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

Two-area system parameters used in simulations are as follows:

$$D_1 = 0.6, D_2 = 0.9, H_1 = 10, H_2 = 8,$$
$$R_1 = 0.05, R_2 = 0.0625,\ \tau_{g1} = 0.2 \text{ s}, \tau_{g2} = 0.3 \text{ s},$$
$$\tau_{T1} = 0.5 \text{ s},\ \tau_{T1} = 0.6 \text{ s}, B_1 = 20.6, B_2 = 16.9,$$
$$\Delta P_{L1} = 0.2, \Delta P_{L2} = 0$$

7. References

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