Stability Delay Margin Computation of Load Frequency Control System with Demand Response

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Abstract— **This paper investigates the impact of dynamic demand response (DR) loop including a communication time delay on the stability delay margin of a single-area load frequency control (LFC) system considering both gain and phase margins (GPMs). A gain-phase margin tester (GPMT) is added to the DR loop of the LFC system as to include GPMs in the calculation of stability delay margins. A direct method in the frequency-domain is employed to compute stability delay margins in terms of system and controller parameters. For a large range of proportional – integral (PI) controller parameters, time delays for which LFC system with DR loop is both stable and has required stability margin quantified by GPMs are determined. Simulation results that delay margins should be computed by taking into account of both gain and phase margins to achieve faster damping of oscillations, less overshoot and settling time.**

Keywords—communication time delay, demand response, frequency regulation, stability delay margin

I. Introduction

The main goal of the conventional Load Frequency Control (LFC) systems is to regulate the frequency around a desired value in an interconnected power system. The system frequency is regulated by matching generation and demand [1]. On the other hand, renewable energy (RE) sources such as wind power, photovoltaic (PV) and fuel cells will have a substantial portion of power generation as distributed generation sources in the future smart power grid [2], [3]. Therefore, the conventional LFC systems get more complicated in terms of frequency regulation. Besides, highly variable generations such as wind power and PVs are unsatisfactory to maintain frequency at its desired value. Energy storage devices and responsive loads are essential for stability of future power grids and for balancing between load demands and power generations [3]-[6].

Due to disadvantages of the renewable energy such as the high costs, low efficiency, power fluctuation, variability and uncertainty of wind and solar resources, dynamic demand response (DR) which plays an important role in providing ancillary services on conventional power plants should be considered as an option in frequency regulation [7, 8]. DR is designed for contributing in energy load reduction and stability of power grid during times of peak demand. When demand is high and supply is inadequate or is the opposite, frequency of interconnected power grid cannot be at its desired value. Additionally, DR increases flexibility and reliability of interconnected power systems, decreases the operational cost and enhances the efficiency of system. To avoid unwanted effects of renewable energy, conventional LFC system is modified using DR loop [8, 9].

The real-time DR applications allow the system to cope with the intermittent nature of RE sources by varying responsive loads in order to match power generation and loads. The integration of DR control loops into LFC system needs a communication network to send control signals and receive measurement data from DR load aggregators. For this purpose, an open distributed communication network is generally used. However, uncertain time delays are observed in such a communication network [9, 10]. These delays can cause instability of power system against an expectation that DR applications having fast-response characteristics can improve the LFC performance. Therefore, it is essential to analyze the delay-dependent stability of LFC system enhanced by a DR loop (LFC-DR) and to determine maximum allowable time delay known as stability delay margin that guarantees the desired dynamic response of the LFC-DR system.

The existing studies that integrate the DR loop with communication delay into the LFC system implement the Padé approximation approach for the transfer function of the time delay in the dynamic analysis and do not present any results on the stability delay margins. This paper implements a frequency-domain exact method to compute stability delay margins of a single-area LFC-DR system considering GPMs. Recent work on the stability of LFC systems with time delay mostly emphasizes on the calculation of delay margin for a selected set of controller gains. These methods could be classified as frequency-domain direct methods [11-16] and time-domain indirect methods. The main objective of frequency domain methods is to determine all critical purely imaginary roots of the characteristic equation and corresponding time delays for which the system will be marginally stable. The indirect time-domain methods that utilize linear matrix inequalities (LMIs) techniques and Lyapunov stability theory have been used to estimate delay margins of the LFC systems [17-19].

Determining the delay margin for a given set of controller values at which the LFC system is marginally stable is considered as the only design parameter in the existing literature. But, a practical LFC-DR system will not be able to operate near those points because of unwanted oscillations in the frequency response. More importantly, a small increase in the time delay could stabilize the LFC-DR system if the time delay is around the delay margin. In order to obtain the desired dynamic performance like; settling time, damping, steady-state error, etc., additional design considerations such as gain and phase margins must be taken into account along with delay margins computation. A

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simple approach has been presented in [20] to investigate the time delayed system's phase and gain margins with adjustable parameters by adding a gain-phase margin tester (GPMT) to the control system's feedforward branch.

This paper is an extension of the previous work presented in [11] determining the delay margins depending upon phase and gain margins. To serve the purpose, the original system is modified to add a GPMT independent of frequency. This can be expressed as a "virtual compensator" in the DR loop of the original LFC system. The inclusion of GPMT will provide appropriate phase and gain margins to the LFC system having delay. Using the exact method [11, 14], first the delay margins values at which the modified LFC-DR system with GPMT will be marginally stable are calculated for a various controller gains. Then, the frequencies of roots crossing over the $j\omega_c$-axis and thereby communication delay values for the LFC-DR system without GPMT are analytically determined. Results obtained from time domain simulations show that in order to achieve an improved frequency response in terms of less settling time, overshoot and oscillations, gain and phase margins must be taken into account for analyzing the delay-dependent stability of LFC-DR systems.

II. Single-Area LFC Sytem Model With DR Loop And GPMT

The conventional LFC system is modified to include a DR loop as an ancillary service in addition to the supplementary control loop. Fig. 1 shows the block diagram of the LFC-DR system. Observe that total time delays in the DR loop are lumped into a single constant delay to simplify stability analysis and an exponential transfer function $e^{-s\tau}$ is introduced in the DR control loop [8, 9]. With the DR accessible in the LFC system, the necessary control work called Ω is allocated between supplementary and DR loops as follows:

$$\begin{aligned}\Delta P_S(s) &= \alpha\Omega \\ \Delta P_{DR}(s) &= (1-\alpha)\Omega\end{aligned} \tag{1}$$

where α is a sharing factor $(0<\alpha<1)$ that determines weight of secondary control or DR control. If the sharing factor is $\alpha=1$, only the secondary control contributes to the frequency regulation. On the other hand, if the sharing factor is selected as $\alpha=0$, it implies that only the DR loop provides the necessary control action. all the required control would be provided by the DR control.

The variables $\Delta P_G, \Delta P_T, \Delta f$ and ΔP_L in Fig. 1 represent valve position, the mechanical output, the deviation of frequency, and load, respectively. The system parameters H, D, T_g, T_t and R are the moment of inertia of the generator, generator damping coefficient, time constant of the governor, time constant of the turbine, and speed drop, respectively.

The user defined GPMT as a "virtual compensator" is added to the DR loop of the LFC system as shown in Fig. 1. The GPMT independent of the frequency is given as:

$$C(A,\phi) = Ae^{-j\phi} \tag{2}$$

where A is gain margin and ϕ represent phase margin.

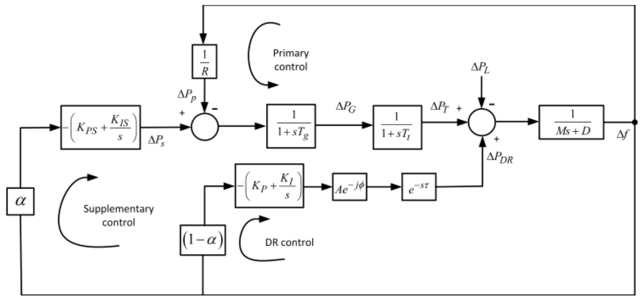

Fig. 1. Block-diagram representation of single area-LFC system model with a DR control loop and GPMT.

For GPMs based stability analysis, the characteristic equation of the LFC-DR system with time delay is required. The characteristic equation of the modified LFC-DR system shown in Fig. 1 having GPMT is given as:

$$\Delta(s,\tau) = P(s) + Q(s)e^{-s\tau}e^{-j\phi} = 0 \tag{3}$$

where

$$\begin{aligned}
&P(s) = p_4 s^4 + p_3 s^3 + p_2 s^2 + p_1 s + p_0, \\
&Q(s) = q_3 s^3 + q_2 s^2 + q_1 s + q_0, \\
&p_4 = MRT_gT_t, p_3 = MRT_g + MRT_t + DRT_gT_t, \\
&p_2 = MR + DRT_g + DRT_t,\ p_1 = 1 + DR + K_{PS}R\alpha, \\
&p_0 = K_{IS}R\alpha,\ q_3 = AK_PRT_gT_t(1-\alpha), \\
&q_2 = AK_PRT_g(1-\alpha) + AK_PRT_t(1-\alpha) \\
&\qquad + AK_IRT_gT_t(1-\alpha), \\
&q_1 = AK_PR(1-\alpha) + AK_IRT_g(1-\alpha) \\
&\qquad + AK_IRT_t(1-\alpha), \\
&q_0 = AK_IR(1-\alpha).
\end{aligned}$$

In order to obtain a compact form of the characteristic equation in (3), the exponential terms $e^{-s\tau}$ and $e^{-j\phi}$ need to be combined into a single exponential term of $e^{-s\tau_c'}$ for $s = j\omega_c$ which is the complex root of (3) on the imaginary axis as follows:

$$\Delta(s,\tau') = P(s) + Q(s)e^{-s\tau'} = 0 \tag{4}$$

The relationship between τ_c' and τ is given as

$$\tau' = \tau + \frac{\phi}{\omega_c} \tag{5}$$

It is to be noted that the time delay value τ_c' is not the delay margin value of the actual LFC-DR system having no GPMT. In fact, τ_c' is the delay margin of the modified LFC-DR system having GPMT. Corresponding to this value, the characteristic polynomial in (4) of the new modified system given in Fig. 1 will have roots on the $j\omega_c$-axis. Hence, the purely imaginary roots of this modified LFC-DR system and delay margins τ_c' needed to be determined first. By utilizing these values, the time delay margin at which the original

LFC-DR system will have desired GPMs, A and ϕ, could be easily calculated using (5).

III. Computation of GPMs Based Stability Delay Margin

The stability of the LFC-DR system having GPMT in the feedforward branch is determined by the roots location of (4). For a given time delay, all the roots should be located in the left half of the s-plane for asymptotic stability. It is to be noted that there is an exponential term in (4) in the form of $e^{-s\tau_c'}$. This exponential term makes the computation of the roots of characteristic polynomial quite difficult as there are infinitely many finite roots. The main goal here is to calculate the delay for which (4) has roots (if any) on the $j\omega_c$-axis. If it is assumed that $\Delta(j\omega_c,\tau_c')=0$ has a root on the $j\omega_c$-axis for some finite values of τ_c', the equation $\Delta(-j\omega_c,\tau_c')=0$ will also have the same root at $j\omega_c$-axis for the same value of τ_c' as complex roots always occur as a conjugate pair. This leads to the solution that by computing the values of τ_c' such that both $\Delta(j\omega_c,\tau_c')=0$ and $\Delta(-j\omega_c,\tau_c')=0$ have the identical root on the $j\omega_c$-axis will give the delay margin value. The result is expressed as [11, 14]:

$$\begin{aligned}\Delta(j\omega_c,\tau_c') &= P(j\omega_c)+Q(j\omega_c)e^{-j\omega_c\tau_c'}=0\\ \Delta(-j\omega_c,\tau_c') &= P(-j\omega_c)+Q(-j\omega_c)e^{j\omega_c\tau_c'}=0\end{aligned} \tag{6}$$

Between two equations in (6), one could easily eliminate $e^{-j\omega_c\tau_c'}$ and $e^{j\omega_c\tau_c'}$ terms and acquire a new characteristic polynomial having no delay terms.

$$W(\omega_c{}^2)=P(j\omega_c)P(-j\omega_c)-Q(j\omega_c)Q(-j\omega_c)=0 \tag{7}$$

By inserting $P(s)$ and $Q(s)$ polynomials of (3) into (7), the modified polynomial for the LFC-DR system having GPMT can be given as;

$$W(\omega_c{}^2)=t_8\omega_c{}^8+t_6\omega_c{}^6+t_4\omega_c{}^4+t_2\omega_c{}^2+t_0=0 \tag{8}$$

where

$$\begin{aligned}&t_8=p_4{}^2, t_6=-2p_4p_2+p_3{}^2-q_3{}^2\\ &t_4=2p_4p_0-2p_3p_1+p_2{}^2+2q_3q_1-q_2{}^2\\ &t_2=-2p_2p_0+p_1{}^2+2q_2q_0-q_1{}^2, t_0=p_0{}^2-q_0{}^2\end{aligned} \tag{9}$$

The procedure clearly indicates that no approximation has been used in eliminating the exponential terms. Thus, positive real roots of (8) i.e. $\omega_c>0$ exactly comply with the imaginary roots of (4) i.e. $s=\pm j\omega_c$. The computation of positive real roots of (8) is relatively easy when compared with the calculation of purely imaginary roots of (4). The delay-independent stability or delay-dependent stability can be characterized by the roots of (8) as:

(i) The modified LFC-DR system having GPMT will be delay-independent stable such that there are no positive real roots of the polynomial in (8) for all finite delays $\tau_c'\geq 0$. This indicates that all roots of (4) are in the left half of the s-plane for all $\tau_c'\geq 0$.

(ii) Whereas, the system will be delay-dependent stable when the polynomial in (8) has at least one positive real root. The presence of such roots indicates that the roots of (4) cross the $j\omega_c$-axis for a finite delay τ_c', called as delay margin.

After finding a real root of (8), the delay margin of the new LFC-DR system including GPMT is computed by (4) and is given as [11, 14]:

$$\begin{aligned}\tau_c' &= \frac{1}{\omega_c}Tan^{-1}\left(\frac{\mathrm{Im}\left\{\dfrac{P(j\omega_c)}{Q(j\omega_c)}\right\}}{\mathrm{Re}\left\{-\dfrac{P(j\omega_c)}{Q(j\omega_c)}\right\}}\right)\\ \tau_c' &= \frac{1}{\omega_c}Tan^{-1}\left(\frac{a_7\omega_c{}^7+a_5\omega_c{}^5+a_3\omega_c{}^3+a_1\omega_c}{a_6\omega_c{}^6+a_4\omega_c{}^4+a_2\omega_c{}^2+a_0}\right)\end{aligned} \tag{11}$$

where the corresponding coefficients are given as

$$\begin{aligned}&a_7=p_4q_3, a_6=p_4q_2-p_3q_3, a_5=p_3q_2-p_4q_1-p_2q_3,\\ &a_4=-p_4q_0-p_2q_2+p_1q_3+p_3q_1,\\ &a_3=-p_1q_2-p_3q_0+p_2q_1+p_0q_3,\\ &a_2=p_2q_0+p_0q_2-p_1q_1, a_1=p_1q_0-p_0q_1\end{aligned}$$

Finally, the delay value for which the LFC-DR system not including GPMT will have the required phase and gain margins can be easily computed after finding the stability delay margin of the LFC-DR system with GPMT. This delay value is given as:

$$\tau_{GPM}=\tau_c'-\frac{\phi}{\omega_c} \tag{12}$$

IV. Results

In this section, delay margins considering gain and phase margins are computed for different PI controller gains. The accuracy of theoretical delay margin results is authenticated by Matlab/Simulink [21]. The LFC-DR system parameters used in the study are given as [8]:

$$\begin{aligned}&T_t=0.4, T_g=0.08, R=3.0, D=0.015, M=0.1667\\ &K_{PS}=0.15, K_{IS}=0.15.\end{aligned}$$

A. Theoretical Stability Delay Margin Results

In order to demonstrate the delay margin computation, sharing factors, PI controller gains and gain and phase margin parameters are first selected as $\alpha=0.4$, $K_P=0.4, K_I=0.6$ and $A=2, \phi=15°$, respectively. The process of the gain and phase margin based delay margin computation consists of the following four steps:

Step 1: Determine the characteristic equation of time delayed LFC-DR system with GPMT using (3). This equation is found to be:

$$\begin{aligned}&\Delta(s,\tau_c')=0.016s^4+0.2415s^3+0.5217s^2+1.225s+0.18+\\ &(0.046s^3+0.76s^2+2.4768s+2.16)e^{-s\tau_c'}=0\end{aligned}$$

Step 2: Obtain the augmented characteristic equations of the LFC-DR system including GPMT using (7) as follows:

$$W(\omega_c^2) = 0.00026\omega_c^8 + 0.04\omega_c^6 - 0.664\omega_c^4 - 1.54\omega_c^2 - 4.63 = 0$$

The characteristic equation without transcendental term given above has a real positive root, $\omega_c = 4.1766$ *rad/s*.

Step 3: Compute the delay margin value of the LFC-DR with GPMT using (11) as follows:

$$\tau_c' = \frac{1}{\omega_c} Tan^{-1}\left(\frac{0.0074\omega_c^7 + 0.12\omega_c^5 - 0.15\omega_c^3 + 2.2\omega_c}{0.001\omega_c^6 + 0.22\omega_c^4 - 1.77\omega_c^2 - 0.39}\right) = 0.3168\ s$$

Step 4: Compute time delay value of the actual LFC-DR system having the desired phase and gain margins using (12) for $\omega_c = 4.1766$ *rad/s*, $\tau_c' = 0.3168\ s$ and $\phi = 15^0 = 0.2616$ *rad*:

$$\tau_{GPM} = 0.3168 - \frac{0.2616}{4.1766} = 0.2541\ s$$

Delay margins ensuring the desired phase and gain margins are calculated by using Steps 1-4 for various values of controller parameters and for numerous phase and gain margins. Table I presents the delay margins for $\phi = 0^0$ and $A = 1$. If the phase and gain margins are not considered, the traditional stability delay margin computation corresponds to this scenario. As seen from (12), $\tau_{GPM} = \tau_c'$ as $\phi = 0^0$. Results show that with an increase in K_I for a fixed K_P, τ_{GPM} tends to decrease. This shows that the increment in K_I values causes a relatively less stable system.

Next, phase and gain margins are chosen as $(A = 2, \phi = 0^0)$ to examine the effect of the gain margin on the delay margin. The results are shown in Table II. Clearly, the delay margins for all PI controller gains are significantly reduced with an addition of gain margin. The phase margin ϕ impact on delay margin of is also investigated. Table III shows the results of delay margin for $(A = 1, \phi = 15^0)$. The results show that while considering the phase margin only, delay margin values decrease for all controller parameters. Though, comparing with the gain margin scenario, the drop in delay margin values is relatively less.

Finally, both phase and gain margins are considered. Table IV presents results for $(A = 2, \phi = 15^0)$. With regards to the gain margin case $(A = 2, \phi = 0^0)$ in Table II and the phase margin case $(A = 1, \phi = 15^0)$ in Table III, it is clear that the phase and gain margins mutual effect on delay margins is significant when compared with their individual effects.

TABLE I. DELAY MARGIN RESULTS FOR $A = 1$ AND $\phi = 0^0$

$\tau_{GPM}(s)$	K_P				
K_I	0.2	0.4	0.6	0.8	1
0.4	2.9741	0.6578	0.4723	0.3864	0.3314
0.6	0.9921	**0.5535**	0.4372	0.3689	0.3210
0.8	0.5362	0.4697	0.4030	0.3512	0.3106
1	0.3961	0.4035	0.3709	0.3337	0.3002
1.2	0.3136	0.3510	0.3415	0.3168	0.2898
1.4	0.2580	0.3088	0.3149	0.3005	0.2796

TABLE II. DELAY MARGIN RESULTS FOR $A = 2$ AND $\phi = 0^0$

$\tau_{GPM}(s)$	K_P				
K_I	0.2	0.4	0.6	0.8	1
0.4	0.4697	0.3512	0.2512	0.2289	0.1936
0.6	0.3510	**0.3168**	0.2646	0.2225	0.1901
0.8	0.2745	0.2850	0.2512	0.2159	0.1865
1	0.2226	0.2569	0.2381	0.2094	0.1829
1.2	0.1856	0.2323	0.2255	0.2028	0.1792
1.4	0.1583	0.2112	0.2135	0.1963	0.1755

TABLE III. DELAY MARGIN RESULTS FOR $A = 1$ AND $\phi = 15^0$

$\tau_{GPM}(s)$	K_P				
K_I	0.2	0.4	0.6	0.8	1
0.4	2.6113	0.5607	0.3957	0.3216	0.2750
0.6	0.8496	**0.4607**	0.3616	0.3045	0.2649
0.8	0.4285	0.3810	0.3286	0.2873	0.2547
1	0.2984	0.3184	0.2979	0.2704	0.2446
1.2	0.2224	0.2691	0.2699	0.2541	0.2345
1.4	0.1716	0.2299	0.2447	0.2385	0.2246

TABLE IV. DELAY MARGIN RESULTS FOR $A = 2$ AND $\phi = 15^0$

$\tau_{GPM}(s)$	K_P				
K_I	0.2	0.4	0.6	0.8	1
0.4	0.3810	0.2873	0.2285	0.1887	0.1600
0.6	0.2691	**0.2541**	0.2154	0.1824	0.1566
0.8	0.1981	0.2239	0.2024	0.1760	0.1530
1	0.1507	0.1973	0.1898	0.1697	0.1495
1.2	0.1175	0.1744	0.1778	0.1633	0.1459
1.4	0.0933	0.1548	0.1665	0.1571	0.1424

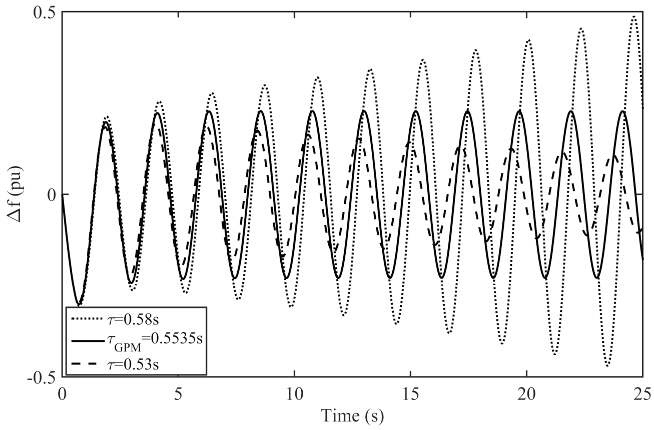

Fig. 2. Frequency deviation for different time delays ($K_P = 0.4, K_I = 0.6$).

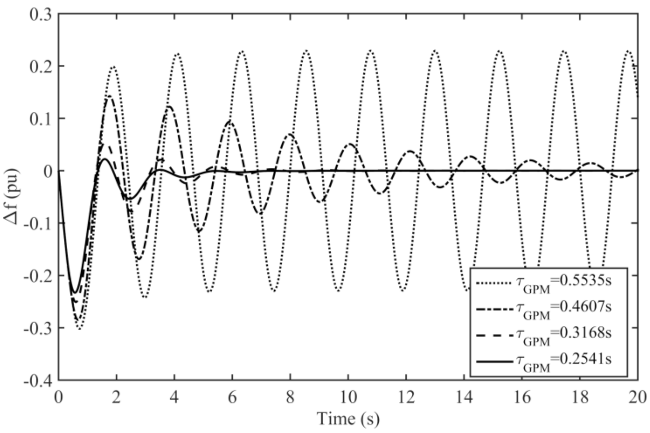

Fig. 3. Damping effect on the frequency response shown by gain and phase margins for $(A=1,\phi=0^0)$, $(A=1,\phi=15^0)$, $(A=2,\phi=0^0)$, $(A=2,\phi=15^0)$ and $(K_P=0.4, K_I=0.6)$.

B. Verfication of Theoretical Stability Delay Margins

The theoretical delay margins are verified using time-domain simulations. The PI controller gains are selected as $K_P=0.4, K_I=0.6$. For the selected controller gain, it is clear from Table I that the delay margin is computed as $\tau_{GPM}=0.5535\,s$ for $(A=1,\phi=0^0)$. Fig. 2 shows frequency response of the LFC-DR system without GPMT for $\tau=0.53\,s$, $\tau_{GPM}=0.5535\,s$ and $\tau=0.58\,s$ at a load disturbance of $\Delta P_d=0.1pu$. The LFC-DR system becomes stable due to decaying oscillations in the frequency response for time delay value of $\tau=0.53\,s<\tau_{GPM}=0.5535\,s$. For $\tau_{GPM}=0.5535\,s$, the LFC-DR system is marginally stable due to sustained oscillations in the frequency response. The LFC-DR system becomes unstable since it has growing oscillations for $\tau_{GPM}=0.5535\,s<\tau=0.58\,s$.

Tables I to IV clearly indicate that for all PI controller gains delay margins decrease when gain and phase margins are considered. For chosen controller gains, $K_P=0.4, K_I=0.6$, the implication of these delay margins can be described as follows: As demonstrated in Table I and Fig. 2, the LFC-DR system only considering stability will be marginally stable at $\tau_{GPM}=0.5535\,s$. This shows that there will be no stability margins for the system in terms of the delay. As illustrated in Fig. 2, a small increase in the time delay $(\tau_{GPM}=0.5535\,s<\tau=0.58\,s)$ can create instability in the LFC-DR system. On the other hand, Table II shows that the system has the GPMs of $(A=2,\phi=0^0)$ at $\tau_{GPM}=0.3168\,s$. This shows that the system is stable as well as it will have the required phase and/or gain margins. In this case, the system remains stable if even a slight rise in the delay is observed.

Time-domain simulations are performed to illustrate the reason why the phase and/or gain margins should be taken into account for delay margin calculations. Load disturbance of $\Delta P_d=0.1pu$ is considered at $t=0$. Fig. 3 compares the frequency responses of the original system for $(A=1,\phi=0^0),(A=1,\phi=15^0),(A=2,\phi=0^0),(A=2,\phi=15^0)$ and $(K_P=0.4, K_I=0.6)$. It is to be noted from Table I that delay margin is found as $\tau_{GPM}=0.5535\,s$ for $(A=1,\phi=0^0)$. It can be seen in Fig. 2 that sustained oscillations are exhibited by the LFC-DR system for this delay value. However, such an oscillatory behavior in the frequency deviations is not tolerable for practical operation of the system.

To remove such an unwanted oscillatory behavior, phase and/or gain margins needed to be considered in delay margin calculation. Tables II, III and IV present delay margins depending upon phase and gain margins that are computed as $\tau_{GPM}=0.3168\,s$ for $(A=2,\phi=0^0)$, $\tau_{GPM}=0.4607\,s$ for $(A=1,\phi=15^0)$ and $\tau_{GPM}=0.2541\,s$ for $(A=2,\phi=15^0)$. When compared with the case of $(A=1,\phi=0^0)$, it can be seen in Fig. 3 that oscillations rapidly damped out for $\tau_{GPM}=0.3168\,s$ when the gain margin $(A=2,\phi=0^0)$ is taken into account. It is to be observed that the oscillations damped out in a same manner for the phase margin scenario, $(A=1,\phi=15^0)$. However, the time taken by the oscillation is relatively longer. Finally, mutual impact of phase and gain margins on the damping in the frequency deviations for $(A=2,\phi=15^0)$ is presented in Fig 3. From Table IV, the delay margin is computed as $\tau_{GPM}=0.2541\,s$. It can be observed from Fig. 3 that oscillations quickly damped out in a shorter time when GPMs are considered.

V. Conclusions

This paper has implemented a frequency domain exact method to compute delay margins considering both normal stability and gain-phase margins. GPMs based stability delay margins have been determined for a large number of controller parameters and gain phase margins. Clearly, the simulation results show that phase and/or gain margins must be added to the delay margin calculation for a better dynamic response (less settling time, less overshoot, fast damping, etc.) of the LFC-DR system having time delays. In the future, multiple DR loops with incommensurate time delays will be included in the LFC systems and a comprehensive delay-dependent stability analysis will be carried out.

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