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An Approximate Model of Load Frequency Control Systems with Time Delay

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Abstract: In this paper we present an approximate model for load frequency control system with time delay. The load frequency control is one of the conventional power system control problems. In order to secure the stability of the grid the frequency must remain within its limited range which is achieved through the load frequency control. The load frequency control signals experience time delay that could destabilize the power systems. The presence of the time delay complicates the analysis of the load frequency control system. In this paper we present a stability method based on the Direct Frequency Response approximation for the time delay. This approximation transforms the transcendental time delay equation into linear equation. This results in a simple stability criterion for the load frequency control system with time delay. A one-area load frequency control system is chosen as a case study. The effectiveness of the proposed approximation has been tested through simulation and comparison with the published research work. By tracking the eigenvalues or using Routh's criterion the maximum delay margin can be estimated. The proposed stability criterion has been compared with the most recent methods and showed it is merit. The range of the PI controller parameters for a given time delay can be determined which is very important in practice.

Keywords: Solar powered, irrigation, fertigation, arduino

1. Introduction

The loads and the demands in a power system network must be matched in real-time to achieve a stable operation and maintain a constant power output within a certain area. An unmatched load and demand may result in a change in system frequency and instability. Therefore, it is crucial to maintain the system frequency at a nominal frequency with a very small margin. One way to solve this is using a load frequency control (LFC) system. Load frequency control is achieved by measuring the frequency of the system. Based on the measured frequency, the system may detect some imbalance and compensate for the change in frequency. The LFC system is used for maintaining the frequency at a nominal frequency, distributing the load between the generators and regulating the tie-line interchange schedule [1]. These tasks are realized by sending the automatic generation control (AGC) signals through dedicated communication links. If those links fail, voice communication through telephone lines may also be used [2].

Area control error (ACE) and generator control error (GCE) signals are distributed between the different areas to maintain a uniform frequency [3]. One major problem in using these communication links is the unavoidable existence of the time delay. This is especially true if open communications are used in the power system [4]. Depending on the type of the communication links, different time delays may be observed due to different reasons and their magnitudes may vary. Power lines, fibre-optics, telephone lines and satellites are the communication links used in power systems nowadays [5].

The performance of the power system may be affected tremendously by the existence of the time delay. In the worst-case scenario, it may also cause instability and thus faults and blackouts may occur. The problem of time delay in

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the LFC system has been extensively researched in the past decade. The stabilization of the LFC system with time delay has been researched comprehensively and the reader may refer to [6-15] for more details. In this paper, we present an approximated model for the LFC system with time delay. The approximate model can also be used for delay margin estimation. The delay margin is defined as the maximum time delay for system stability. Lyapunov–Krasovskii theorem and tracking the eigenvalues in the s-domain are the two main approaches used in the published research. Less conventional delay margins are obtained using the s-domain methods with constant time delay. The impact of the time delay on the stability of the LFC system is simulated in [2]. In [2], constant time delays and random time delays are studied. It was concluded that a longer time delay could lead to LFC system instability. However, the calculation of delay margin or the stabilisation of the LFC system with time delay was not included by the authors.

In [16], a set of linear matrix inequalities (LMIs) are solved to compute the delay margin for single-area and multi-area LFC systems. By replacing the time delay terms with the Newton-Leibnitz formula, solving Lyapunov–Krasovskii functionals and introducing free weighting matrices (FWMs), the LMIs can be derived [17]. The conservativeness of the delay margin values is reduced by the introduction of FWMs. The proportional-integral (PI) controller parameters are also varied to investigate the effect on the delay margin. An enhanced and less conservative criterion for calculating the delay margin was introduced in [18]. Lyapunov–Krasovskii functional, Wirtinger inequality and Jensen integral inequality were also applied to bind the derivative of the Lyapunov function. According to [15] and [19], the number of decision variables was lower than in [16] which lead to less conservative results for the delay margin.

In [13], a simple LMI stability criterion was applied to compute the delay margin. However, the delay margins from the results were very conservative. An improved delay-dependent stability method of load frequency control system was presented in [20]. A time derivative bounded by truncated second-order Bessel–Legendre (B-L) inequality was used for the Lyapunov–Krasovskii functional. Using the binary iteration algorithm, the LMIs are then solved. The results were less conservative. In [21], a hybrid method was used for delay margin computation. Using a constant time delay margin criterion, a robust PI controller was derived by applying a robust LMI method. The stability criterion for the LFC system with two-time delays was derived in [22]. This is achieved through the use of the Lyapunov–Krasovskii functional along with the Jensen inequality and the extended reciprocally convex matrix inequality. According to [23], energy storage units could improve the LFC system performance. In [24], a multi-area LFC system with plug-in electric vehicles and communication delay was studied. A robust PID controller was derived using the particle swarm optimization and the linear matrix inequalities techniques. This was also applied in [25] where it is used to handle the inertia uncertainty and the time-varying communication delay. In this case, the uncertain time-delay system model consists of an LFC system with the electric vehicles (EVs) and the communication delay. In [26], the delay margin was calculated using the Lyapunov–Krasovskii functional with the Wirtinger-based improved integral inequality for an LFC system with electric vehicles.

In this paper, the literature focus is only on the problem of the delay margin computation for an LFC system. For a comprehensive review for the stabilisation of the LFC system, the reader can refer to [27-29]. A direct method for computing the delay margin is presented in [30]. The transcendency in the characteristic equation was eliminated using Rekasius substitution and then it is converted to a polynomial. The imaginary roots for positive delays were tracked and then the time delay margin was determined using the Routh–Hurwitz stability criterion. However, the results were less conservative than in [16]. Furthermore, there is an increasing complexity for multiple time-delay systems which is one of the drawbacks of the method used. In [31], the PI controller parameters for a single-area LFC system was determined for a given time delay and also satisfied a stability criterion. An exact method for computing the delay margin was presented in [32] by transforming the transcendental equation to a normal polynomial in jω. The conservativeness of the results was reduced as the analysis was carried out in the frequency domain without any approximation. The exponential terms were excluded and the transcendental equation was converted to a frequency-dependent equation. The numbers of frequencies that cross the imaginary access are finite. In [33-34], the sweeping test and the binary iteration algorithm are used to determine the delay margin. The results of the delay margin using the sweeping test are very accurate, however, their calculation involves solving complex nonlinear frequency-dependent equation using the spectral frequency as a measure.

In this paper, we present a delay margin estimation method for the LFC system by using an approximation of the time delay term. The advantage of using this method is that the equations become less complex and yet it still gives accurate results to a certain degree. This is important for the method to be used in practice. Compared to the literature discussed above, the proposed method is far more simple and easy to use. In the following sections, the approximate model of a single-area LFC system with time delay is described. Then, stability analysis of the LFC system was carried out in the frequency domain using the Routh-Hurwitz criterion. A single-area LFC system was chosen as a case study. The results of the delay margin using the proposed method were compared with the results of the most recent published research.

2. Dynamic Model of One-Area LFC System with Time Delay

The one-area LFC system is shown in Fig. **1**. The main assumption is that all the generators are equipped with non-reheat turbines. The state-space linear model of one-area LFC system is expressed as:

$$x_c(t) = A_c x(t) + B_c u(t) + F_c \Delta P_d \quad (1)$$

$$y(t) = C_c x_c(t) \quad (2)$$

where;

$$A_c = \begin{bmatrix} -\frac{D}{M} & \frac{1}{M} & 0 \\ 0 & -\frac{1}{T_{ch}} & \frac{1}{T_{ch}} \\ -\frac{1}{RT_g} & 0 & -\frac{1}{T_g} \end{bmatrix} B_c = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_g} \end{bmatrix} F_c = \begin{bmatrix} -\frac{1}{M} \\ 0 \\ 0 \end{bmatrix}$$

$$C_c = [\beta \quad 0 \quad 0] \qquad x_c(t) = [\Delta f \quad \Delta P_m \quad \Delta P_v]^T \qquad y_c(t) = ACE$$

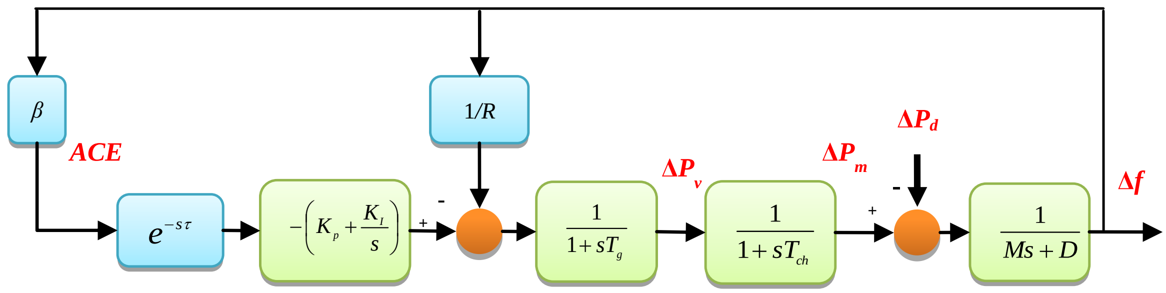

Fig. 1 - A dynamic model of one-area LFC scheme

The parameters are given as ΔP_d is the load deviation, ΔP_m is the generator mechanical output deviation, ΔP_v is the valve position deviation, Δf is the frequency deviation. M is the moment of inertia, D is the generator damping coefficient, T_g is the time constant of the governor, T_{ch} is the time constant of the turbine, R is the speed drop, and β is the frequency bias factor. For a one-area LFC system, the area control error ACE is given as:

$$ACE = \beta \Delta f \quad (3)$$

The AGC has two components; the first is updated every 5 minutes for economical dispatch and the second is updated in the order of 1-5 seconds. The later signal delay is the one considered in the paper. Stabilizing the system with conventional PI controller given as:

$$u(t) = -K_p ACE - K_I \int ACE \quad (4)$$

where K_P is the proportional gain, K_I is the integral gain and $\int ACE$ is the integration of the area control error. The communication delay is represented by $e^{-s\tau}$. The exponential term introduces transcendency in the characteristics equation which makes the solution very complex. The $e^{-s\tau}$ can be represented by the Direct Frequency Response as follows [35]:

$$e^{-s\tau} = \frac{1 - 0.49\tau s + 0.093\tau^2 s^2}{1 + 0.49\tau s + 0.093\tau^2 s^2} = \frac{a_\tau s^2 - b_\tau s + c_\tau}{a_\tau s^2 + b_\tau s + c_\tau} \quad (5)$$

After replacing the exponential term in Fig. 1 and redrawing the simplified LFC system with time delay, a modified block diagram is obtained as shown in Fig. 2. From Fig. 2, the linear model of the LFC with time delay is given as:

$$\Delta \dot{f} = \frac{-D}{M}\Delta f + \frac{1}{M}\Delta P_m - \frac{1}{M}\Delta P_d \quad (6)$$

$$\Delta \dot{P}_m = \frac{-1}{T_{ch}}\Delta P_m + \frac{1}{T_{ch}}\Delta P_v \quad (7)$$

$$\Delta\dot{P}_v = \frac{-1}{T_g}\Delta P_v - \left(\frac{\beta K_P}{T_g} + \frac{1}{RT_g}\right)\Delta f - \frac{K_I}{T_g}\int ACE_\tau + \frac{2K_p b_\tau z_1}{T_g} \tag{8}$$

$$ACE_\tau = \beta\Delta f - 2b_\tau z_1 \tag{9}$$

$$\dot{z}_1 = \frac{\beta}{a_\tau}\Delta f - \frac{b_\tau}{a_\tau}z_1 - \frac{c_\tau}{a_\tau}z_2 \tag{10}$$

$$\dot{z}_2 = z_1 \tag{11}$$

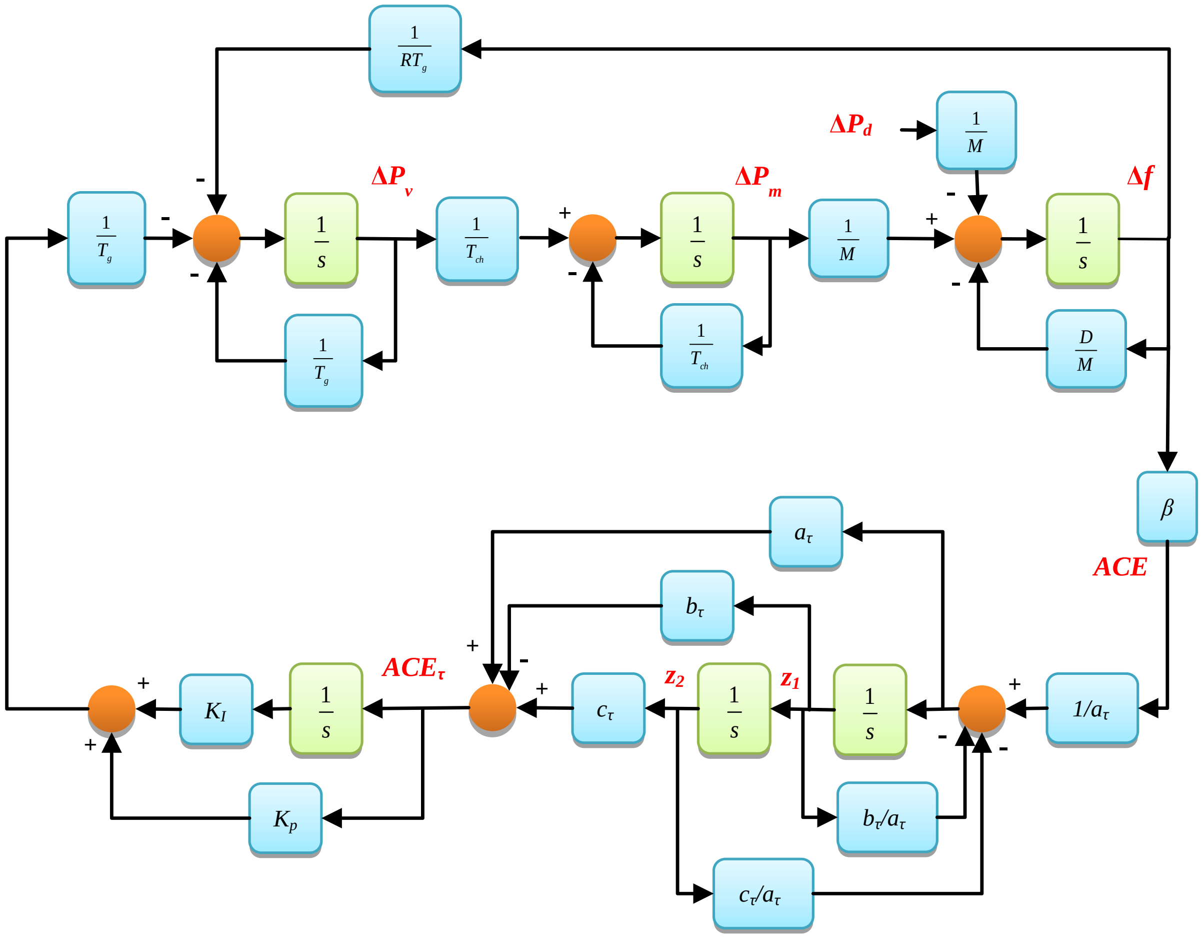

Fig. 2 - Simplified model for LFC with time delay

Equations (6)-(11) can be written in matrix form as:

$$\begin{bmatrix} \Delta\dot{f} \\ \Delta\dot{P}_m \\ \Delta\dot{P}_v \\ ACE_\tau \\ \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} \frac{-D}{M} & \frac{1}{M} & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{ch}} & \frac{1}{T_{ch}} & 0 & 0 & 0 \\ -\left(\frac{\beta K_P}{T_g} + \frac{1}{RT_g}\right) & 0 & -\frac{1}{T_g} & -\frac{K_I}{T_g} & \frac{2K_p b_\tau}{T_g} & 0 \\ \beta & 0 & 0 & 0 & -2b_\tau & 0 \\ \frac{\beta}{a_\tau} & 0 & 0 & 0 & -\frac{b_\tau}{a_\tau} & -\frac{c_\tau}{a_\tau} \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta f \\ \Delta P_m \\ \Delta P_v \\ \int ACE_\tau \\ z_1 \\ z_2 \end{bmatrix} \tag{12}$$

$$\dot{x}(t) = A(\tau)x(t) \tag{13}$$

The LFC system with time delay has been transformed into a linear system with a delay-dependent state matrix. The matrix A(τ) has the time delay as a variable in addition to the LFC system parameters and the PI controller gains. By solving (13) for a given time delay the stability of the LFC system with the time delay could be assessed.

3. Stability Analysis Using Routh-Hurwitz Criterion

The LFC system with the time delay can be represented as:

$$\Delta f = -\frac{Q(s)}{P(s)}\Delta P_d = -\frac{q_5 s^5 + q_4 s^4 + q_3 s^3 + q_2 s^2 + q_1 s + q_0}{p_6 s^6 + p_5 s^5 + p_4 s^4 + p_3 s^3 + p_2 s^2 + p_1 s + p_0}\Delta P_d \tag{14}$$

The polynomials coefficients are given as:

$$q_5 = a_\tau R T_{ch} T_g \;\; q_4 = R[a_\tau (T_{ch} + T_g) + b_\tau T_{ch} T_g] \;\; q_3 = R[a_\tau + T_{ch} T_g + b_\tau (T_{ch} + T_g)] \;,\; q_2 = R[b_\tau + T_{ch} + T_g],$$
$$q_1 = R \;\; q_0 = 0 \;\; p_6 = \mathrm{MRT_{ch} T_g a_\tau}, \; p_5 = MR[a_\tau (T_{ch} + T_g) + b_\tau T_{ch} T_g] + a_\tau D R T_{ch} T_g$$
$$p_4 = MR[a_\tau + c_\tau T_{ch} T_g + b_\tau (T_{ch} + T_g)] + DR[a_\tau (T_{ch} + T_g) + b_\tau T_{ch} T_g]$$
$$p_3 = MR[T_{ch} + T_g + b_\tau] + DR[a_\tau + T_{ch} T_g + b_\tau (T_{ch} + T_g)] + a_\tau (\beta R K_P T_g + 1)$$
$$p_2 = MR + DR[T_{ch} + T_g + b_\tau] + \beta R(a_\tau K_I - 2 b_\tau K_P) + b_\tau + b_\tau R \beta K_P T_g$$
$$p_1 = 1 + DR + \beta R(K_P T_g - b_\tau K_I) \;\; p_0 = \beta R K_I \;,\; a_\tau = 0.093\tau^2 ,\; b_\tau = 0.49\tau \;,\; c_\tau = 1$$

The coefficients of the polynomial determine the response and the stability of the LFC system. The poles of the LFC systems depends on the coefficients p_0-p_6. For a stable system, all the poles should be in the left half-plane of the s-domain. To find the delay margin. In a real LFC system, the proportional gain is usually very small. The coefficients p_0-p_6 with $K_P = 0$ are given as;

$$p_6 = 0.015 a_\tau ,\; p_5 = 0.2015 a_\tau + 0.015 b_\tau ,\; p_4 = 0.52 a_\tau + 0.2015 b_\tau + 0.015 ,$$
$$p_3 = 1.05 a_\tau + 0.52 b_\tau + 0.2015 ,\; p_2 = 1.05 a_\tau K_I + 1.05 b_\tau + 0.52 ,\; p_1 = -1.05 b_\tau K_I + 1.05 ,\; p_0 = 1.05 K_I$$

To determine the delay Routh's criterion is used as follows. Routh table is given as:

s^6	p_6	p_4	p_2	p_0
s^5	p_5	p_3	p_1	0
s^4	R_{41}	R_{42}	R_{43}	0
s^3	R_{31}	R_{32}	0	0
s^2	R_{21}	R_{22}	0	0
s^1	R_{11}	0	0	0
s^0	R_{01}	0	0	0

where;

$$R_{41} = \frac{p_5 p_4 - p_3 p_6}{p_5} ,\; R_{42} = \frac{p_5 p_2 - p_1 p_6}{p_5} ,\; R_{43} = p_0$$
$$R_{31} = \frac{R_{41} p_3 - R_{42} p_5}{R_{41}} ,\; R_{32} = \frac{R_{41} p_1 - p_0 p_5}{R_{41}}$$
$$R_{21} = \frac{R_{31} R_{42} - R_{31} R_{42}}{R_{31}} ,\; R_{22} = R_{43} = p_0$$
$$R_{11} = \frac{R_{21} R_{32} - R_{31} p_0}{R_{21}} ,\; R_{01} = R_{22} = p_0$$

Theorem 1: (Routh-Hurwitz Criterion) [36]
The number of sign changes in the first column of the Routh table equals the number of roots of the polynomial in the Closed Right Half-Plane.

For a stable LFC system, there will be no sign change in the first column in Routh's table. In this case, p_6, p_5, R_{41}, R_{31} R_{21}, R_{11} and R_{01} should have the same sign. This is used as the stability criterion in this paper. If the time delay is larger than the maximum delay margin, then a sign change will be in the first column.

4. One-Area LFC System

The system parameters in [16, 18, 32] are used to compare the results of the proposed method to the other published methods. The parameters of the LFC system shown in Fig. 1 are given as: T_{ch}=0.3, T_g=0.1, R=0.05, D=1.0, β=21.0 and M=10. Through the shared network, the remote terminal unit (RTU) sends the signals to the central controller in the case of an open communication network. Then, the commands are sent back by the controller. The two delays are defined as feedforward and feedback delays. In this paper, these two delays are aggregated into a single delay since most of the studies also stated this assumption. **Error! Reference source not found.** shows the results of delay margins using the proposed method along with the other published methods in [16, 18, 32-33] in which [32-33] provide the most accurate reported delay margins. It is shown that the proposed method closely matches [32-33] with a very small error. However, the proposed method is much simpler with fewer computations needed. Figure 3 shows the different delay margins with the proposed method and [32] for a given integral gain and proportional gain. Again, the delay margins computed using the proposed method gives almost the same values as in [32] with a small error. **Error! Reference source not found.** shows the relative percentage error with different values of K_P and K_I using the proposed method and the method in [32]. As can be seen the relative error is very small. Figure 4 and 5 show the delay margin different PI controller gains with the proposed method and the method in [32]. From Figure 3 the delay margin has the same trend as has been reported in the literature which shows the validity of the approximation over a wide range of values of K_P and K_I. The delay margin decreases with increasing K_P and K_I.

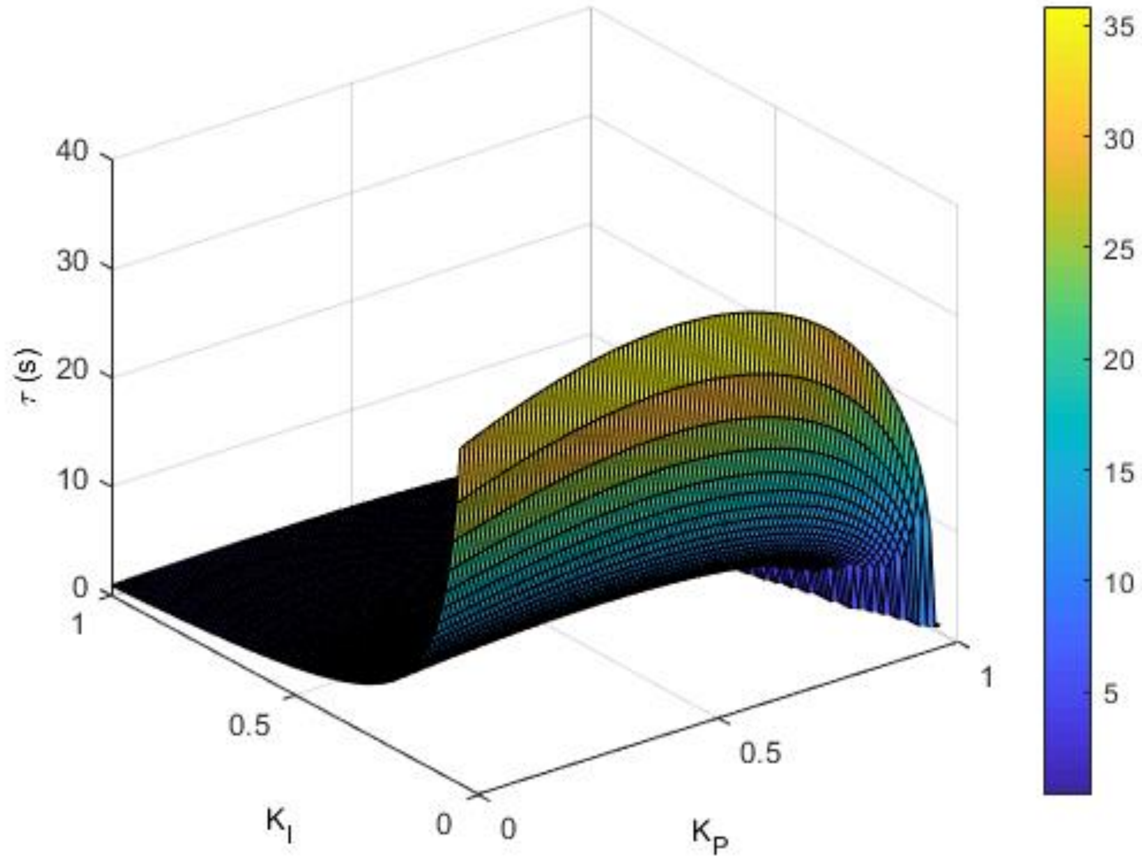

Fig. 3 - The delay margin as a function of the PI controller gains K_P and K_I

Table 1 - The delay margin for different values of K_P and K_I

τ(s)		K_I						
K_p	Method	0.05	0.1	0.15	0.2	0.4	0.6	1.0
0	Theorem 1	30.9444	15.2066	9.9614	7.3375	3.3816	2.0422	0.9230
	[32]	30.915	15.201	9.960	7.335	3.382	2.042	0.923
	[18]	30.853	15.172	9.942	7.323	3.377	2.040	0.922
	[16]	27.927	13.778	9.056	6.692	3.124	1.910	0.886
0.05	Theorem 1	31.8509	15.6870	10.2774	7.5730	3.5018	2.1219	0.9703
	[32]	31.875	15.681	10.279	7.575	3.501	2.122	0.970
	[18]	31.498	15.647	10.258	7.561	3.496	2.119	0.969
	[16]	27.874	14.061	9.284	6.866	3.215	1.974	0.927
0.1	Theorem 1	32.7688	16.1269	10.5750	7.7931	3.6097	2.1940	1.0124
	[32]	32.751	16.119	10.571	7.794	3.610	2.194	1.012
	[18]	30.415	15.765	10.547	7.777	3.604	2.191	1.011
	[16]	27.038	13.682	9.220	6.941	3.290	2.029	0.963
0.2	Theorem 1	34.1982	16.8603	11.0601	8.1604	3.7918	2.3126	1.0785
	[32]	34.226	16.856	11.062	8.162	3.792	2.313	1.079
	[18]	28.010	14.597	10.107	7.821	3.784	2.309	1.077
	[16]	25.114	12.760	8.617	6.535	3.320	2.108	1.016
0.4	Theorem 1	35.8020	17.6612	11.5955	8.5586	3.9805	2.4257	1.1183
	[32]	35.834	17.658	11.594	8.559	3.980	2.426	1.118
	[18]	22.457	11.835	8.287	6.505	3.718	2.419	1.116
	[16]	20.364	10.426	7.065	5.384	2.832	1.912	1.017
0.6	Theorem 1	34.9063	17.1982	11.2799	8.3106	3.8256	2.2812	0.9474
	[32]	34.922	17.195	11.278	8.312	3.826	2.281	0.947
	[18]	16.033	8.624	6.209	4.997	3.038	2.178	0.964
	[16]	14.618	7.477	5.157	3.958	2.130	1.475	0.827
1.0	Theorem 1	0.5954	0.5857	0.5753	0.5643	0.5158	0.4634	0.3610
	[32]	0.596	0.586	0.575	0.564	0.516	0.463	0.361
	[18]	0.594	0.584	0.574	0.563	0.515	0.463	0.360
	[16]	0.546	0.538	0.530	0.522	0.482	0.438	0.348

Table 1 - Relative percentage error of the delay margin

Delay Margin Rel Err %	K_I						
K_p	0.05	0.1	0.15	0.2	0.4	0.6	1.0
0	0.0952	0.1258	0.1475	0.1885	0.3107	0.4984	0.9436
0.05	0.0434	0.0700	0.0990	0.1252	0.2628	0.4049	0.8944
0.1	0.0021	0.0209	0.0452	0.0675	0.1951	0.3335	0.8053
0.2	0.0717	0.0555	0.0391	0.0275	0.0760	0.1885	0.5532
0.4	0.1061	0.1105	0.1119	0.1255	0.0758	0.0232	0.3743
0.6	0.0611	0.0250	0.0102	0.0324	0.1026	0.0977	0.2995
1.0	0.1281	0.2198	0.3458	0.3793	0.4552	0.7426	1.0187

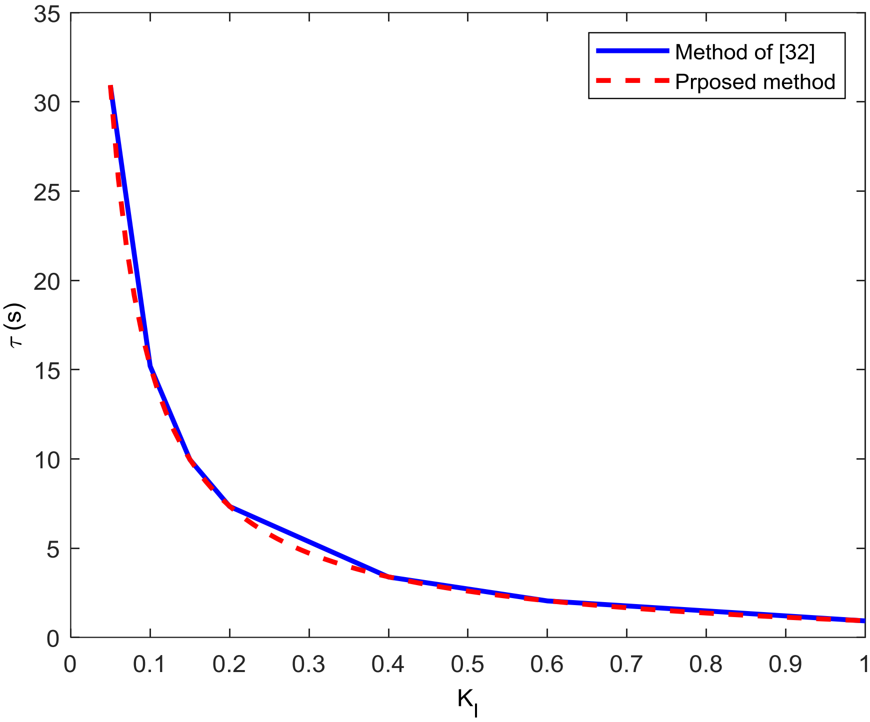

Fig. 4 - Delay margin as a function of the integral gain, K_I with K_P = 0

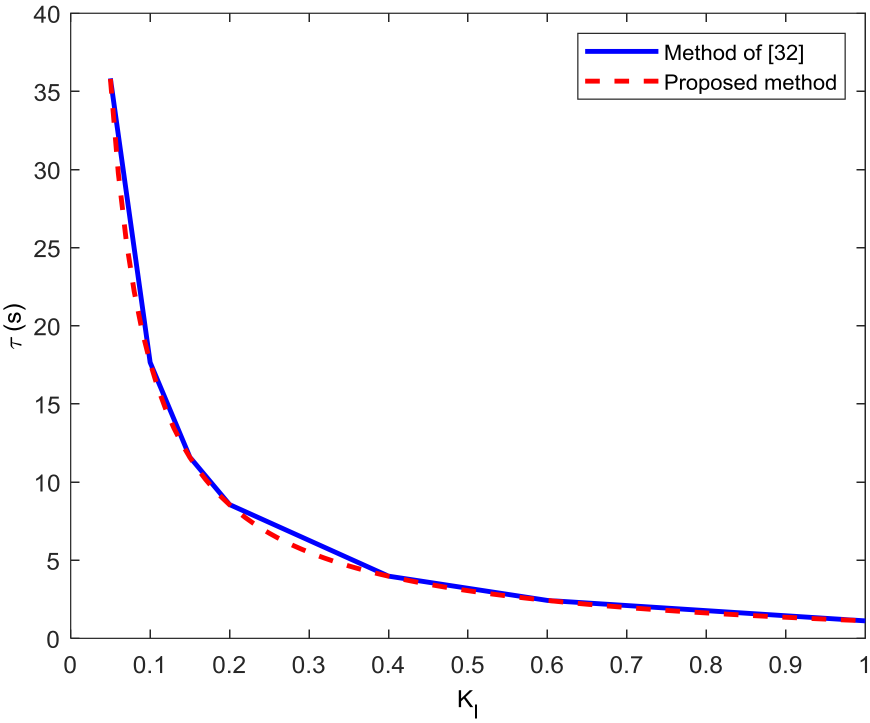

Fig. 5 - Delay margin as a function of the integral gain, K_I with K_P = 0.2

To verify the accuracy of the proposed model, the frequency response of the actual model and the approximated model are compared.

Case I: (K_P = 0 and K_I = 0.4): Simulations with MATLAB/Simulink were carried out to validate the results. While varying the time delay, the frequency deviation of the proposed method and the frequency response using an exact model is compared as shown in 6-10. At t = 10 s, a 0.1 p.u change of load occurs and it is clear that the proposed model follows closely the exact model. Figure 9, shows the response when the system is still stable while Figure 10, shows the response when the system is unstable. In all the cases the approximated model shows a good agreement with the exact model.

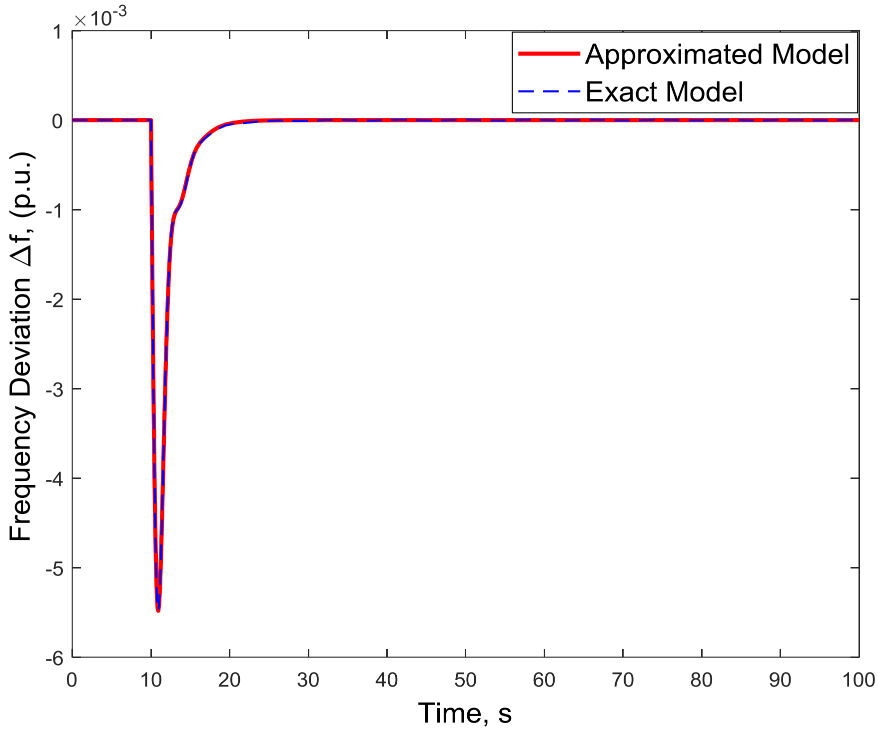

Fig. 6 - The frequency deviation with, K_I = 0.4, K_P = 0 and τ = 0.001 s

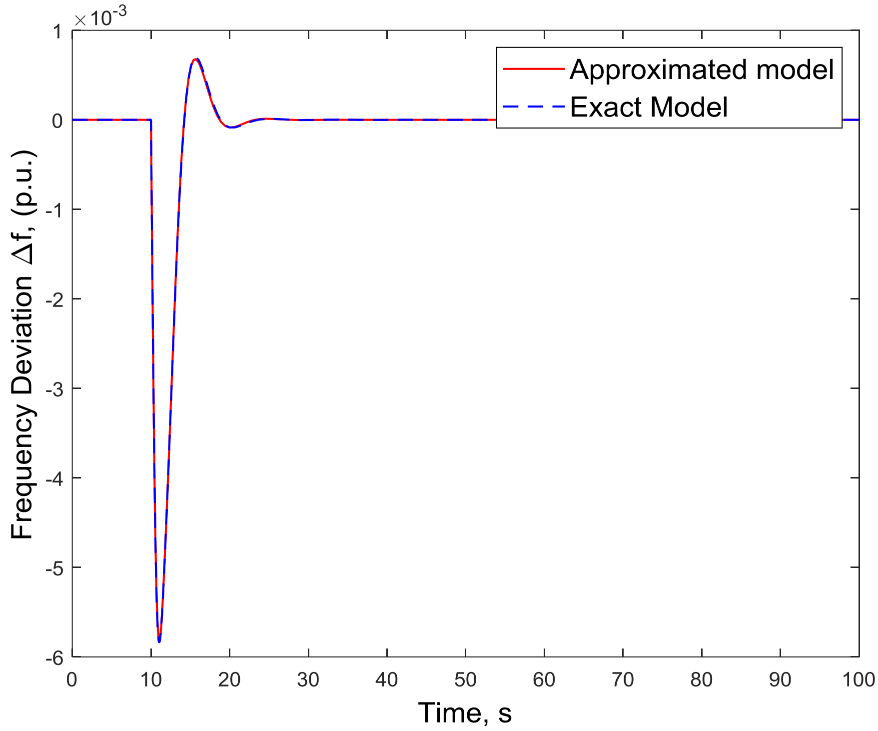

Fig. 7 - The frequency deviation with, K_I = 0.4, K_P = 0 and τ = 1 s

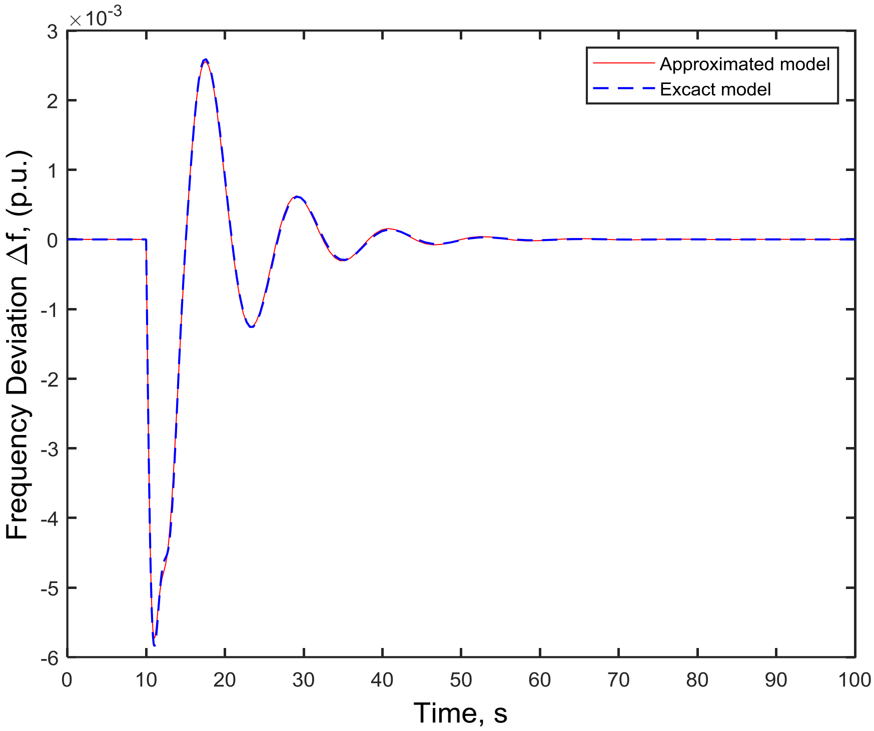

Fig. 8 - The frequency deviation with, K_I = 0.4, K_P = 0 and τ = 2 s

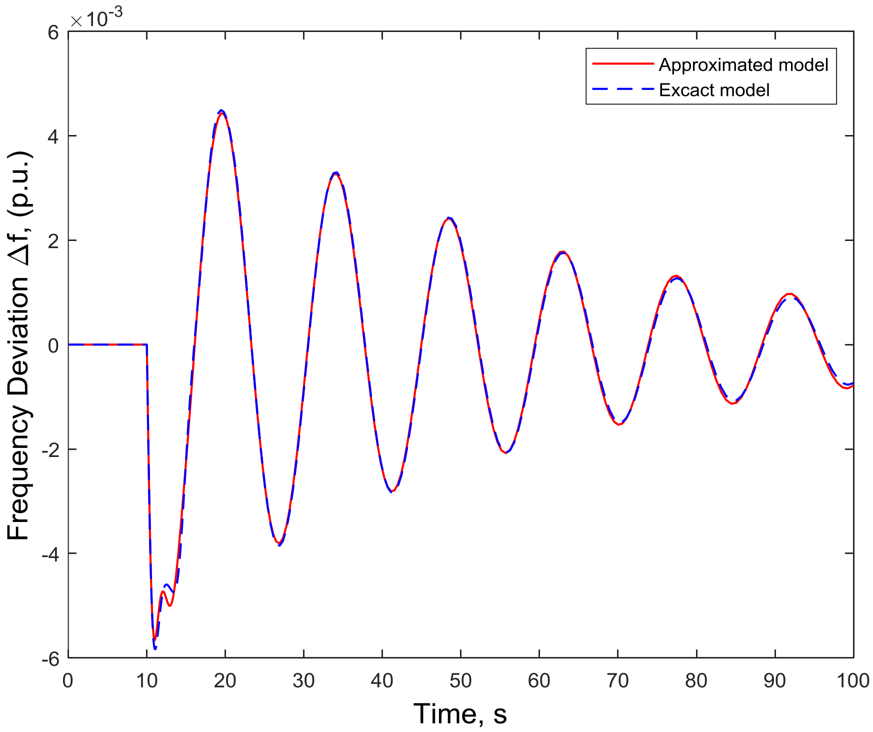

Fig. 9 - The frequency deviation with, K_I = 0.4, K_P = 0 and τ = 3 s

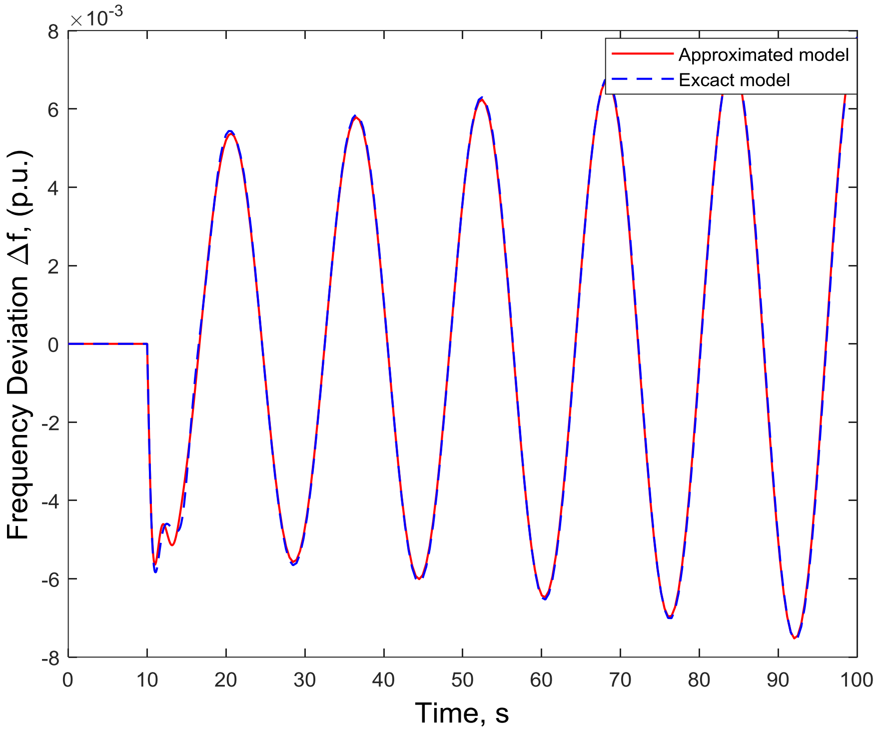

Fig. 10 - The frequency deviation with, K_I = 0.4, K_P = 0 and τ = 3.5 s

From Table 1, the delay margin of the proposed method, when the system has K_P = 0 and K_I = 0.4, is 3.382 s. The system response with different time delays is shown in Fig. 11. The system is stable with 3.3 s time delay, marginally stable with 3.382 s and unstable with 3.4 s as reported in [32-33]. However, the model is approximated, the delay margin results are close to the accurate results.

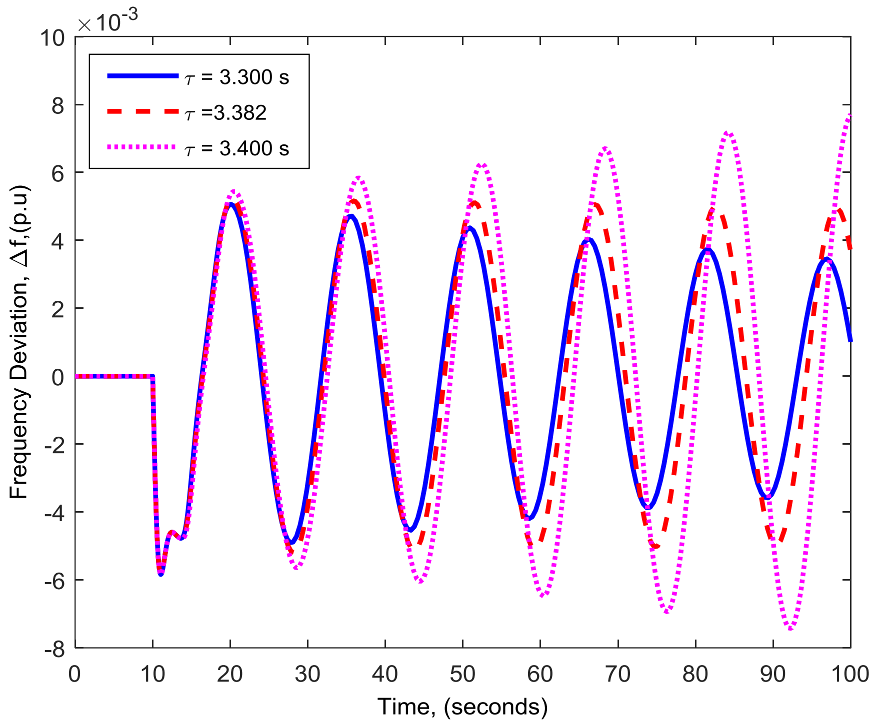

Fig. 11 - The frequency deviation with, K_I = 0.4, K_P = 0 and different time delays

Case II: (K_P = 0.6 and K_I = 1.0):
The frequency deviation with the proposed model and the exact model is almost the same as shown in Figure 12.

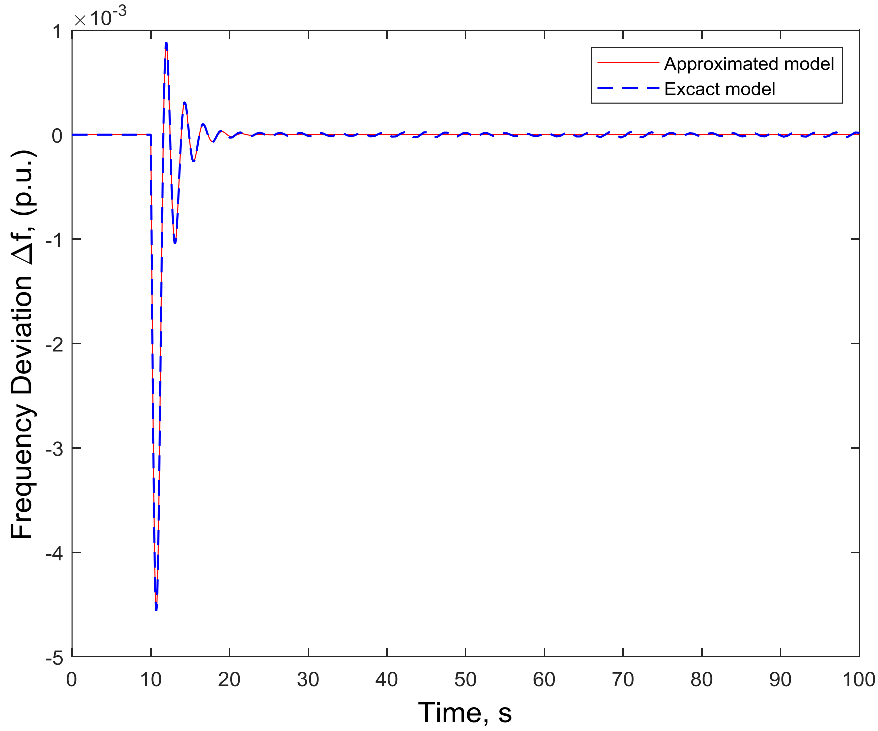

Fig. 12 - The frequency deviation with, K_I = 1.0, K_P = 0.6 and τ = 0.1 s

5. Conclusions

In this paper, we propose a method to calculate the maximum delay margin in load frequency control systems based on the Direct Frequency Response approximation for the time delay. The transcendental time delay equation is converted to a delay-dependent linear equation and the stability of the system is analysed using the Routh-Hurwitz stability criterion. A one-area load frequency control system has been chosen as a case study. The method gives accurate delay margins which are proved by time delay simulation and comparison with the recently published methods. Furthermore, using the proposed method, the range of the PI controller parameters for a given time delay can be determined. The proposed method is only applicable to a load frequency system with a single time delay. The method will be extended in the future to deal with multiple time delays.

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