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Time Delay Margins Computation for Stability of Load Frequency Control in Hybrid Renewable Energy Power Generation/Storage System

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Abstract: In load frequency control (LFC) systems, it is important to transmit control signals from remote terminal units (RTU) to the control center and from the control center to the plant side. Because of this data exchanges, time delays in signal transmission become unavoidable. These delays reduce the dynamic performance of the LFC system and may even destabilize the system. This paper is dedicated to the delay-dependent stability analysis of the LFC scheme containing a renewable energy power generation subsystem. The system under study includes photovoltaic system (PV), ultra-capacitor (UC) bank for energy storage, wind turbine generator (WTG), diesel generator (DG) and fuel cell (FC) system. Using a frequency-domain exact method, stability delay margins of the system are determined theoretically for different values of inertia, damping factor as well as controller gains. The relation between the controller gains and the delay margin is investigated. The upper bound of the delay time for which the LFC system is marginally stable is known as stability delay margin. Theoretical delay margins are verified by time-domain simulation studies. Delay margin computations are realized by using an analytical method approach. Proportional-integral (PI) controller is used for controlling proposed power generation storage system. PI Controller parameters are chosen in a wide range to observe the effect of the parameter space on delay margin variation. Simulation studies verify the effectiveness of the proposed method.
Keywords: Power generation control, Power system stability, Hybrid power systems, Load management, Stability delay margin

Hibrit Yenilenebilir Enerji Güç Üretimi/Depolama Sisteminde Yük Frekansı Kontrolünün Kararlılığı İçin Kararlılık Gecikme Paylarının Hesaplaması

Öz: Yük frekansı kontrolünde (LFC), kontrol sinyallerini kontrol merkezinden tesis tarafına ve uzak terminal ünitelerinden (RTU) kontrol merkezine iletmek önemlidir. Bu, sinyal iletiminde zaman gecikmelerinin olması kaçınılmaz hale gelmektedir. Bu gecikmeler LFC sisteminin dinamik performansını azaltmakta ve hatta sistemi kararsız hale getirmektedir. Bu makale, yenilenebilir enerji üretimi alt sistemi içere LFC sisteminin gecikmeye bağlı olarak kararlılık analizini yapmaktadır. Analizi yapılan sistem fotovoltaik sistem (PV), enerji depolama için ultra-kapasitör (UC) bankası, rüzgâr türbini jeneratörü (WTG), dizel jeneratör (DG) ve yakıt hücresi (FC) sistemini içermektedir. LFC sistemin sınırda kararlı olacağı maksimum zaman gecikme değeri kararlılık gecikme payı olarak bilinmektedir. Frekans düzleminde tanımlı bir analitik yöntem kullanılarak kararlılık gecikme payları farklı atalet değerleri, sönümleme faktörü ve kontrolör kazançları için teorik olarak hesaplanmıştır... Teorik olarak elde edilen sonuçlar benzetim çalışmaları ile karşılaştırılmıştır. Kontrolör kazancı ile gecikme payı arasındaki ilişki incelenmiştir. Gecikme payları, oransal integral (PI) kontrolör kullanılarak geniş bir parametre aralığı için hesaplanmıştır. Bu sonuçlar, PI kontrolörlerini, dinamik performans ile gecikme payı arasında bir uygun değer ayarlaması yapmak için kullanılabilir. MATLAB ortamında yapılan benzetim çalışmaları kullanılan yöntemin etkinliğini doğrulamaktadır.
Anahtar Kelimeler: Güç üretim kontrolü, Güç sistem kararlılığı, Hibrit güç sistemleri, Yük yönetimi, Kararlılık gecikme payı

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1. Introduction

Major power grid blackouts have been occurred in electrical power network in recent years. This tends some countries to use hybrid micro grids. Moreover, many countries and remote areas around the World are utilizing stand-alone power generation systems. There are lots of literature about stand-alone power systems [1]. Due to fuel price risings, pollution and environmental warming, the renewable energy in the form of grid independent system is in raise. In renewable power generation, solar and wind power generation are of the most two attractive methods. Due to weather conditions, solar and wind resources' power production fluctuate. For that reason, energy storage systems or additional generation is generally needed, such as battery bank and FC. Modeling of hybrid renewable energy systems and control of frequency deviation are extensively investigated in literature. Among them, the small signal stability analysis of a hybrid power generation/storage system connected to an isolated load was analyzed [2]. The load frequency control for an isolated small-hydro power plant which applied reduced dump load technique was investigated [3]. FC dynamic model as a first order lead lag was investigated [4]. Transient events based on experimental data were analyzed to indicate how the FC systems exactly behave. The output power control of wind turbine generator by using pitch angle variation, was presented in [5] and [6]. It is well-known in the control system theory that the dynamic performance of closed loop systems could be degraded by time delays. It may even sometimes cause instability of the system [7]. Recently, LFC scheme analysis/synthesis which has communication delays was addressed [8]. Network delay modeling and network communication requirement for a third-party LFC service were investigated and also in deregulated market, the effects of communication delay for the LFC scheme was demonstrated [9]. Also, delay-dependent stability analysis of a traditional LFC scheme was presented [10]. To overcome the impacts of time delay, based on linear matrix inequality (LMI) technique, a decentralized state-feedback controller and a full state-feedback controller were designed [7]. The time delays are treated as multiplicative uncertainties [11] and based on $H\infty$ theory, a decentralized proportional integral type LFC was investigated [11].

Delay margin computations for dynamical systems with time delays are achieved mainly by two types of theoretical methods. The first one is based on frequency domain approaches which aim to determine roots of system's characteristic equation or critical eigenvalues. Those direct methods common beginning point is that characteristic equations' imaginary roots determination [12-14]. Basic applications of this method had developed for analyzing constant time delays. The second group of methods is time-domain approaches that implement LMI technique and Lyapunov stability theory to identify stability delay margins. In [8] stability that depends on delay, analyzed for frequency control of loads which have constant and time-varying delays. Linear matrix inequality method was applied [10] for load frequency control which has communication delay. The existing studies reported by Sönmez, et al. [15] indicate that frequency-domain direct methods result in more accurate delay margins as we compare with the time-domain methods.

This paper implements a theoretical method represented by [12] to identify the stability delay margins of hybrid renewable energy systems with constant communication time delays. The hybrid system is composed of photovoltaic system (PV), ultra-capacitor (UC) bank for energy storage, wind turbine generator (WTG), diesel generator (DG) and fuel cell (FC) system. Firstly, dynamic model of hybrid LFC system reported by [16] has been enhanced by taking into account all communication time delays. For investigation of quantitative effect of the controller, delay margins are calculated for different values of proportional integral controller gains. Finally, theoretical delay margin result accuracy computed by the proposed method and the results are verified by utilizing simulations. To the best knowledge of the authors, delay margin computation of such a hybrid system has not been reported in the literature. The main contributions of this work can be summarized as follows: i) Stability delay margin computation of the hybrid LFC system using a frequency domain exact method not having any approximations, ii) Extensive investigation of the impact of the PI controller gains on the stability delay margin.

The general outline of the paper is arranged as follows. In Section II, the investigation of the problem and the formulation of dynamic model of LFC scheme are realized. In Section III, under the hybrid LFC scheme with time delays, derivations of sufficient conditions for the stability of the power systems are presented. Based on controller parameters, case studies are carried out in Section IV. Finally, comments on results and conclusions are given in Section V.

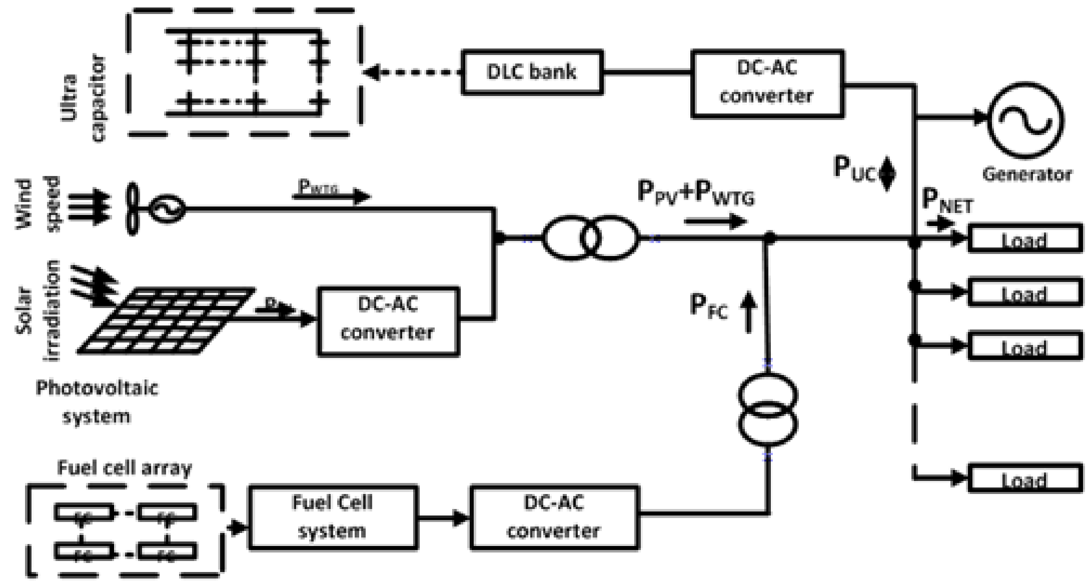

Figure 1. Configuration of the hybrid power system

2. Time Delayed Hybrid LFC System

Figure 1 shows the hybrid power generation/energy storage system configuration under study. This configuration is known as micro grid system. If this system is going to be controlled by a remote controller, there would be communication time delays. Therefore, control commands send by the remote center could not be executed on time. This condition may destabilize the power system. The time delay that destabilize the power system is known as stability delay margin. This delay margin is the main focus of this paper. By looking at the controller gain parameters KI-KP, one can see how long the command send form control center to UC and FC could be delayed. If command receiving time of UC and FC are more than calculated delay margin than power system will be in an unstable position. The generation subsystems comprise a PV, a WTG, a FC and an UC. Observe that for exchanging energy with the analyzed AC system, only PV, FC and UC require suitable power converters. The capacity of UC is assumed enough to store excess energy that is generated by subsystems.

The block diagram of the hybrid LFC system is shown in Figure 2. Net power generation PNET is determined by: (a) the output power of the PVs (PPV), (b) a part of the output power from the WTGs (PWTG) (c) the output power of DC–AC converter which is connected to the FCs (PFC), (d) the power exchange of the UCs (PUC), and the output power of generator(PGEN). The hybrid LFC scheme conventional model is revised/modified by the time delay inclusion into the control mechanism. As a controller, proportional-integral control is used for controlling load frequency in the model. The LFC scheme may have multiple delays. These multiple delays are represented as constant single delay to preserve simplicity of the system. By using this assumption, building a simple model is possible as shown in Fig. 2. The model provides an appropriate portrayal of a single time delay which comprised in state variables. In the proposed system, to reduce discharging and charging of DLC bank in long-term, a high-pass filter (HPF) is also used. With the help of HPF, the overall system frequency deviation is divided into two parts. Compensation of high frequency deviation is suppressed by DLC banks, due to it has fast response time. FC system is used to compensate low frequency deviation [16].

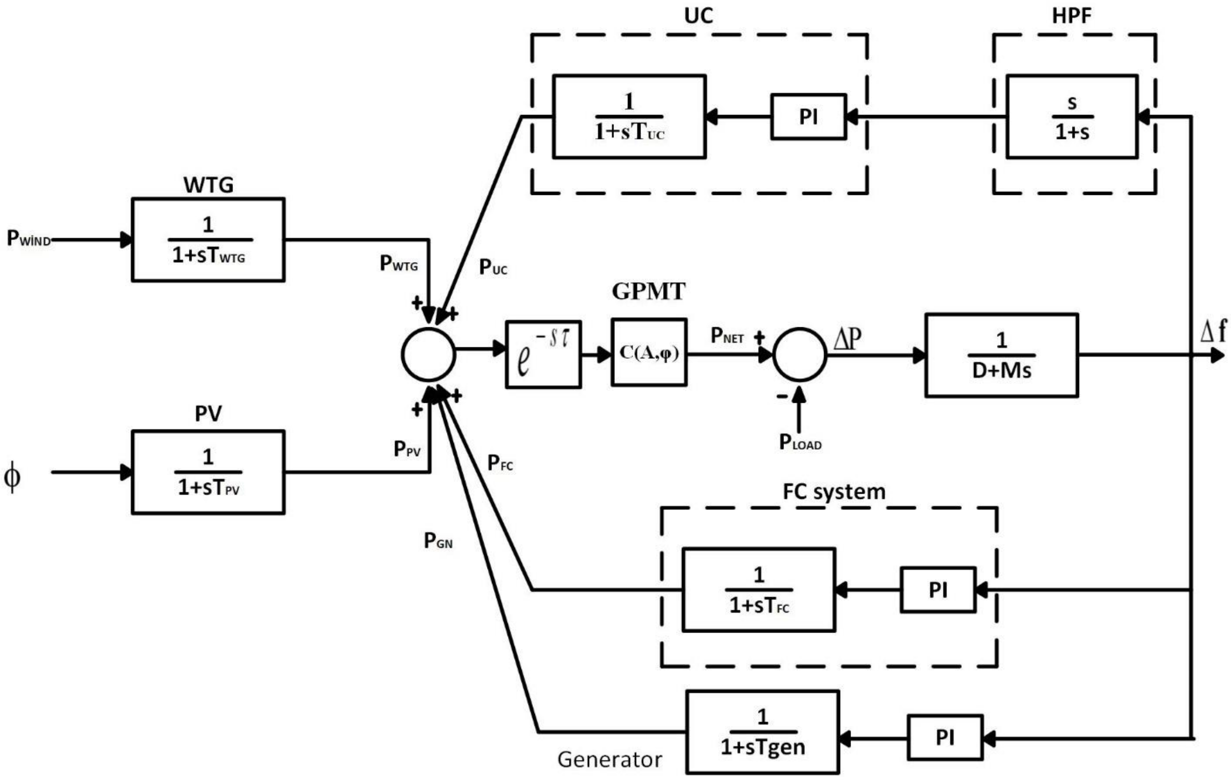

Figure 2. Hybrid power system block diagram for investigation.

For delay margin computation, the characteristic equation for time-delayed hybrid LFC system in Fig. 2 is first obtained as follows:

$$\Delta(s,\tau) = P(s) + Q(s)e^{-s\tau} = 0 \quad (1)$$

where τ stands for total time delay, $Q(s)$ and $P(s)$ are real coefficient polynomials in s which is given below:

$$P(s) = p_6 s^6 + p_5 s^5 + p_4 s^4 + p_3 s^3 + p_2 s^2 \quad (2)$$
$$Q(s) = q_4 s^4 + q_3 s^3 + q_2 s^2 + q_1 s \quad (3)$$

where
$$\begin{aligned}
p_6 &= MT_{FC}T_{UC} \\
p_5 &= MT_{FC}T_{UC} + MT_{FC} + MT_{UC} + DT_{FC}T_{UC} \\
p_4 &= MT_{FC} + MT_{UC} + M + DT_{FC}T_{UC} + DT_{FC} + DT_{UC} \\
p_3 &= M + DT_{FC} + DT_{UC} + D \\
p_2 &= D \\
q_4 &= K_P T_{FC} + K_P T_{UC} \\
q_3 &= K_I T_{FC} + 2K_P + K_I T_{UC} + K_P T_{UC} \\
q_2 &= 2K_I + K_I T_{UC} + K_P \\
q_1 &= K_I
\end{aligned} \quad (4)$$

The roots location of the characteristic equation (1) should be founded to compute stability delay margins of hybrid LFC system with time delay. In the following section, the direct method based on the elimination of exponential term is applied to the characteristic equation of (1).

3. Delay-Dependent Stability Analysis

The characteristic equation of dynamical systems with time delays is infinite dimensional at an equilibrium point due to presence of exponential terms. For that reason, it is difficult to extract the stability maps of system. That means, eigenvalues of the system are infinite. However, it is not needed to find all roots of characteristic equation given by (1) for stability analysis of the hybrid LFC system. It is enough to evaluate how characteristic equation of the system varies with respect to time delay. For the delay-free system (i.e., τ=0), stability of LFC system relies on the system's characteristic equation's roots locations which is defined by equation (1). It is clear that those roots are the function of τ that is time delay. When τ changes, some of roots location may change. Let's assume that the roots of characteristic equation are on imaginary axis that is at s=jw_c, for some bounded time delay. Here, subscript c stands for "crossing frequency". As it is known from control theory that complex roots have the symmetry of complex conjugate and thusfor some value of time delay τ, the equation Δ(-s,τ)=0 must have same root at s=jw_c. For this reason, the problem reduces to calculating values of time delay τ, such that both Δ(s,τ)=0 and Δ(-s,τ)=0 share same common roots at s=jw_c . This condition can be formulated by the following equations,

$$\Delta(s,\tau) = P(s) + e^{-s\tau}Q(s) = 0 \tag{5}$$
$$\Delta(-s,\tau) = P(-s) + e^{s\tau}Q(-s) = 0 \tag{6}$$

For the elimination of exponential term in (5) and (6), we replace s with $s = \pm jw_c$,

$$\Delta(jw_c,\tau) = P(jw_c) + e^{-jw_c\tau}Q(jw_c) = 0 \tag{7}$$

$$\Delta(-jw_c,\tau) = P(-jw_c) + e^{jw_c\tau}Q(-jw_c) = 0 \tag{8}$$

After application of exponential term elimination method, characteristic equation becomes,

$$W(w_c^2) = P(jw_c) * P(-jw_c) - Q(jw_c) * Q(-jw_c) = 0 \tag{9}$$

When we replace Q(s), P(s) values in equation (2) and (3) into equation (9) the following new type of polynomial is obtained which has no exponential terms.

$$W(w_c^2) = t_{12}w_c^{12} + t_{10}w_c^{10} + t_8w_c^8 + t_6w_c^6 + t_4w_c^4 + t_2w_c^2 = 0 \tag{10}$$

where t_i's are functions of p and q coefficients as given below

$$\begin{aligned}
t_{12} &= p_6^2 \\
t_{10} &= -2 * p_4 * p_6 + p_5^2 \\
t_8 &= 2 * p_2 * p_6 - 2 * p_3 * p_5 + p_4^2 - q_4^2 \\
t_6 &= -2 * p_2 * p_4 + 2 * q_2 * q_4 + p_3^2 - q_3^2 \\
t_4 &= p_2^2 + 2 * q_1 * q_3 - q_2^2 \\
t_2 &= -q_1^2
\end{aligned} \tag{11}$$

The stability problem is reduced effectively by this method to the one that delay free. That means, problem is only reduced to computing roots of a single-variable polynomial of (10). Notice that the 6th order characteristic equation with exponential terms in equation (1) is now transformed into a 12th order polynomial shown by equation (10) without having any exponential terms. The real positive roots of (10) matches with the magnitude of equation (1) imaginary roots, $s=\mp jw_c$ exactly. To calculate of positive real roots of equation (10) is much easier than calculation of purely imaginary roots of equation (1).

The delay dependency of hybrid LFC system can be easily determined by the positive real roots of the new polynomial of (10). The hybrid system is said to be delay-independent stable, if the modified characteristic equation (10) does not contain any real positive root for all delays $\tau \geq 0$. when the modified characteristic equation (10) has at least one positive real root, then hybrid LFC system is said to be delay-dependent stable. The existence of such roots means that equation (1) roots crosses the imaginary axis at $s=\mp jw_c$ for a limited delay τ.

The method of [12] is used for the time delay margin computation for the proposed LFC system.

$$\tau^* = \frac{1}{w_c} tan^{-1}\left(\frac{k_9 w_c^9 + k_7 w_c^7 + k_5 w_c^5 + k_3 w_c^3}{k_{10} w_c^{10} + k_8 w_c^8 k_6 w_c^6 + k_4 w_c^4}\right) \tag{12}$$

where

$$\begin{aligned} k_{10} &= p_6 * q_4\,, \\ k_8 &= -p_4 * q_4 + p_5 * q_3 - p_6 * q_2, \\ k_6 &= p_2 * q_4 - p_3 * q_3 + p_4 * q_2 - p_5 * q_1 \\ k_4 &= -p_2 * q_2 + p_3 * q_1 \end{aligned} \tag{13}$$

When the roots of equation (10) is positive, then we also need to check whether the root of equation (1) is crossing the imaginary axis at $s = jw_c$, while τ is increasing. This can be verified by looking at the sign of real part of $[ds/d\tau]$. If the critical characteristic roots pass the imaginary axis with velocity different than zero, then there must be some roots which are passing through the imaginary axis. These roots are given by

$$Re\left[\frac{ds}{d\tau}\right]_{s=jw_c} \neq 0 \tag{14}$$

$$RT|_{s=jw_c} = sgn[W'(w_c^2)] \tag{15}$$

where the prime stands for derivative of equation (10) with respect to w_c^2. The derivation the equation (15) can be found in [17]. The consequence of this expression gives a simple criterion. This criterion implies the transition direction of the roots at $s=jw_c$. when τ is increased from $\tau_1=\tau^*-\Delta\tau$ to $\tau_2=\tau^*+\Delta\tau$, $0 < \Delta\tau << 1$, the transition direction can be obtained. When root tendency is RT= -1, the root $s=jw_c$ crosses the imaginary axis to stable left half-plane. When root tendency is RT= +1,, the root $s=jw_c$ crosses the imaginary axis to unstable right half-plane. For single- delay case, the equation (10), have only finite number of positive real roots for all $\tau \in \mathbb{R}^+$. Let us call this set

$$\{w_c\} = \{w_{c1}, w_{c2}, \dots, w_{cp}\} \tag{16}$$

for each w_{cm}, m = 1, 2 ,….. ,p we may get many τ^*_m values which are spaced periodically by using equation (12).Let this set be called

$$\{\tau_m^*\} = \{\tau_{m1}^*, \tau_{m2}^*, \dots, \tau_{m\infty}^*\}\; m = 1,2, \dots, p \tag{17}$$

where $\tau_{m,r+1} - \tau_{m,r} = \frac{2\pi}{w_c}$ is the obvious period of repetition. Taking into account delay margin definition, the minimum of τ_m^* , m=1, 2, 3,…., p is the systems' delay margin $\tau^* = \min(\tau_m^*)$.

Table 1. Delay margin results for different PI controller parameters, damping factor of the load and inertia. (M=0.4, D=0.03)

τ*(s)	**K_I**									
KP	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
0.5	0.517	**0.334**	0.233	0.172	0.132	0.104	0.083	0.068	0.056	0.046
1	0.338	0.297	0.259	0.226	0.198	0.174	0.154	0.137	0.123	0.111
1.5	0.246	0.232	0.218	0.205	0.192	0.179	0.167	0.157	0.146	0.137
2	0.196	0.189	0.183	0.176	0.170	0.164	0.157	0.151	0.145	0.139
2.5	0.164	0.160	0.157	0.153	0.150	0.146	0.142	0.139	0.135	0.132
3	0.141	0.139	0.137	0.135	0.133	0.130	0.128	0.126	0.124	0.122
3.5	0.125	0.123	0.122	0.120	0.119	0.117	0.116	0.114	0.113	0.111
4	0.111	0.110	0.109	0.108	0.107	0.106	0.105	0.104	0.103	0.102
4.5	0.101	0.100	0.099	0.098	0.098	0.097	0.096	0.095	0.095	0.094
5	0.092	0.091	0.091	0.090	0.089	0.089	0.088	0.088	0.087	0.087

Table 2. Results of Delay margin for $0 \leq K_I \leq 1$ and $0 \leq K_P \leq 1$, M=0.4, D=0.03

τ*(s)	**K_I**						
KP	**0.05**	**0.1**	**0.15**	**0.2**	**0.4**	**0.6**	**1**
0	1.0783	0.6490	0.4616	0.3502	0.1502	0.0739	0.0111
0.05	1.9799	1.1165	0.7773	0.5888	0.2716	0.1555	0.0605
0.1	2.5201	1.4691	1.0338	0.7906	0.3819	0.2319	0.1080
0.2	2.2097	1.6227	1.2546	1.0130	0.5489	0.3595	0.1986
0.4	1.0081	0.9483	0.8865	0.8254	0.6181	0.4755	0.3088
0.6	0.6298	0.6139	0.5974	0.5804	0.5116	0.4470	0.3426
1	0.3732	0.3694	0.3657	0.3618	0.3461	0.3300	0.2977

Table 3. Delay margin results for different PI controller parameters, damping factor of the load and inertia. (M=0.8, D=0.03)

τ*(s)	**K_I**									
KP	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
0.5	0,849	0,472	0,310	0,222	0,166	0,128	0,101	0,081	0,065	0,052
1	0,646	0,510	0,405	0,329	0,272	0,229	0,195	0,169	0,147	0,129
1.5	0,458	0,413	0,369	0,330	0,294	0,263	0,237	0,214	0,194	0,177
2	0,355	0,335	0,315	0,295	0,276	0,257	0,240	0,224	0,210	0,196
2.5	0,293	0,282	0,271	0,260	0,249	0,238	0,227	0,217	0,207	0,198
3	0,251	0,245	0,238	0,231	0,224	0,217	0,211	0,204	0,197	0,191
3.5	0,221	0,217	0,212	0,208	0,203	0,199	0,194	0,189	0,185	0,180
4	0,198	0,195	0,192	0,189	0,186	0,182	0,179	0,176	0,173	0,170
4.5	0,180	0,178	0,176	0,173	0,171	0,169	0,166	0,164	0,161	0,159
5	0,165	0,164	0,162	0,160	0,158	0,157	0,155	0,153	0,151	0,149

4. Case Studies

The delay margins are calculated for hybrid LFC system. For investigation of the quantitative effect of the controller, margins for delay are investigated for broad range of values of PI controller gains. Also, by utilizing simulation studies, verification of accuracy of delay margin is realized. The system parameters are chosen as follows; T_{PV}, time constant for PV system: 1.8 sec. ; T_{WTG}, time constant for WTG system: 1.5 sec.; T_{FC}, time constant for FC system: 0.26 sec; T_{UC}, time constant for UC system: 0.01 sec. . The damping factor of the load is D and it is chosen as % 3. Total inertia M, is chosen as 0.4 pu. A positive ΔP_d=0.1 pu load disturbance is applied to LFC system and then at t=0 s, the frequency response of hybrid LFC system is obtained.

Table 4. Delay margin results for different PI controller parameters, damping factor of the load and inertia. (M=0.4, D=0.1)

τ^*(s)	K_I									
KP	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
0.5	0,557	0,363	0,256	0,191	0,148	0,118	0,096	0,079	0,066	0,055
1	0,351	0,310	0,272	0,238	0,208	0,184	0,163	0,146	0,131	0,118
1.5	0,253	0,239	0,225	0,212	0,198	0,186	0,174	0,163	0,152	0,143
2	0,200	0,194	0,188	0,181	0,175	0,168	0,162	0,156	0,149	0,144
2.5	0,167	0,164	0,160	0,157	0,153	0,149	0,146	0,142	0,139	0,135
3	0,144	0,142	0,140	0,138	0,135	0,133	0,131	0,129	0,126	0,124
3.5	0,127	0,125	0,124	0,122	0,121	0,120	0,118	0,117	0,115	0,114
4	0,113	0,112	0,111	0,110	0,109	0,108	0,107	0,106	0,105	0,104
4.5	0,102	0,101	0,101	0,100	0,099	0,099	0,098	0,097	0,096	0,096
5	0,093	0,092	0,092	0,091	0,091	0,090	0,090	0,089	0,089	0,088

Computation of delay margins are done using equation (12) for a large number of PI controller gains. These are demonstrated in Table I. For this table, the damping factor of the load, D=0.03, and inertia M=0.4 pu. are held constant. One can see from table that if K_P fixed, τ* declines as K_I increases.

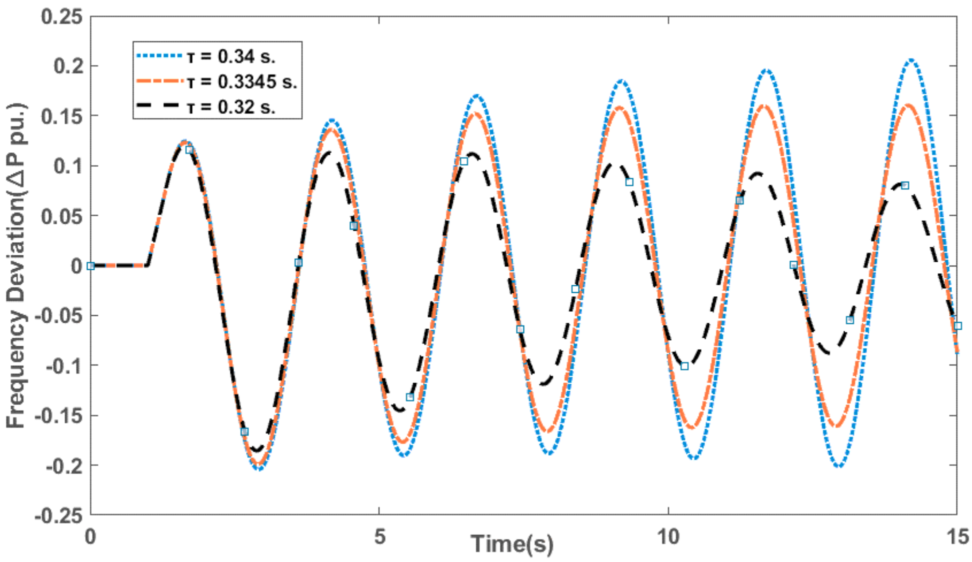

Figure 3. Deviation of load frequency versus time delays (K_I=1, K_P= 0.5, τ*=0.3345)

This shows that when the K_I increases, it results in a hybrid LFC system with reduced stability. When K_P is fixed, the impact of KI on τ* is that increasing K_I decreases τ*. Detailed analysis can be done for the interval of 0≤ K_I ≤1 and 0≤ K_P ≤1. The behavior of τ^* with respect to K_P and K_I values for this interval is shown in Table 2. Results indicate that for a fixed K_P, τ* decreases as K_I increases. When K_P is fixed, the impact of K_I on τ* is that increasing K_I decreases τ*. The effect of K_P on the delay margin τ* has two results for fixed K_I. The first trend is that, delay margin τ*

increases as K_P increases in between interval of $0 \leq K_P \leq 0.1$. But, when $0.1 < K_P$, the delay margin declines while K_P increases.

The effect of the damping factor and inertia of the load on delay margin is analyzed in Table 3 and Table 4. For Table 3, the damping factor of the load, D=0.03, and inertia M=0.8 pu. are taken and held constant. For Table 4, the damping factor of the load, D=0.1, and inertia M=0.4 pu. are taken and held constant. If the tables are compared, one can observe that increasing inertia M, increases delay margin τ^*. Increasing or decreasing damping factor has no significant impact on delay margin τ^*.it only changes oscillation amplitude.
Verification of the theoretical delay margins are realized by simulations in time-domain. The verification of the results of theoretical delay margin are performed in Matlab/Simulink environment for time-domain simulations. Typical parameters for PI controller gains in Figure 3 chosen as: K_I=1 K_P= 0.5. Note that for that PI gains, theoretical delay margin is computed as τ^*=0.334s which is shown in Table 1.

The simulation results in Figure 3 shows where the hybrid system is marginally stable at τ =0.3345s. due to the sustained oscillations. Also, for τ =0.32 s, the LFC system is stable with decreasing oscillations. It is unstable for τ >0.335 s. with inclining oscillations. The theoretical delay margins are exactly the same as one obtained by simulation, which indicates effectiveness of the suggested method.

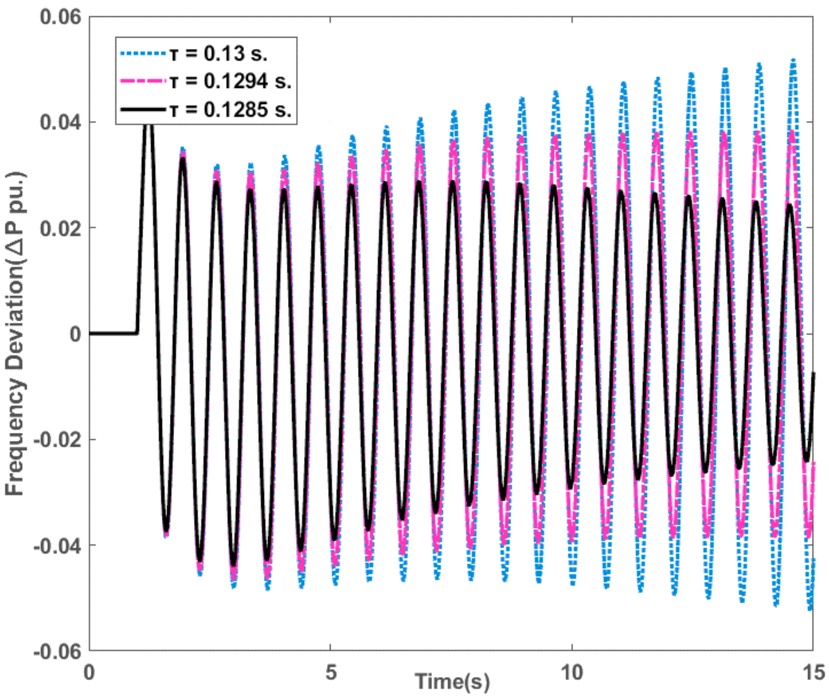

Figure 4. Frequency deviation for different time delays (K_I=3.5, K_P=3, τ^*=0.1287)

In Figure 4 the typical parameters of PI controller are, K_I=3.5 K_P=3 and theoretical delay margin τ^*=0.128 s. The simulation results presented in figure 4 indicates that the hybrid system is marginally stable at τ=0.1294 s. due to the sustained oscillations. Also, please note that for τ=0.1285s, the hybrid LFC system is stable with decreasing oscillations. It is unstable for τ > 0.1295 s. with growing oscillations.

It is clear from both Figs. 3 and 4 that, the suggested method approximates the delay margins of the hybrid LFC system with high accuracy. For example, in table 1, for K_I=3.5 K_P=3, time delay τ^* is calculated as τ^*=0.128 sec. In Figure 4 simulation result shows that for τ^*=0.1294 s. the hybrid LFC system is marginally stable. This result is compatible with the theoretical result. Also, for τ^*=0.13 sec (bigger than delay margin), it can be seen in Figure 4 that the hybrid system is unstable which is compatible with the theoretical result.

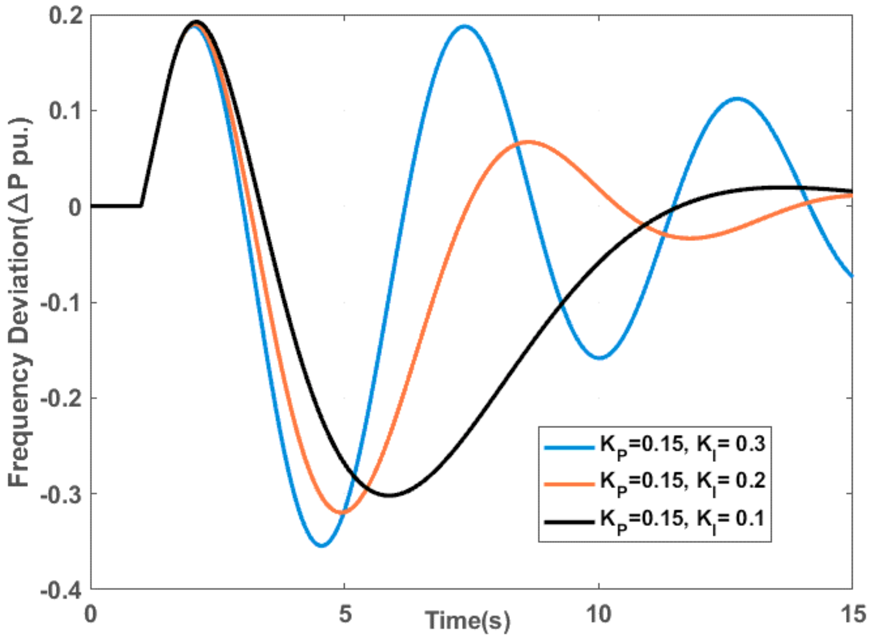

Figure 5. Frequency deviation for different controller gains (τ = 0.5sec)

Finally, in Figure 5, taking K_P=0.15 as constant and by varying the K_I values between, 0.1<K_I<0.3 the frequency deviation is observed. It can be seen that increasing K_I value, results in an increase in oscillation durations.

5. Conclusions

Stability analysis of a hybrid LFC scheme that depends on delay has been investigated by taking into account of communication channels' time delays. Hybrid system components are enriched by adding UC and FC systems which differs from previous studies. In the literature, there is no article examining the effects of the parameters we analyzed by using the selected system components.

The conventional hybrid LFC scheme has been considered as a linear system that has time delays which is operated with a PI-type controller. After then the stability criterion that depends on delay has been used to find the delay margins. The method eliminates the characteristic equation's exponential terms in such a way that the polynomial gives positive real roots which corresponds to crossing frequency values. Crossing frequency is a frequency at which stability attribute of the system changes. Case studies are investigated based on PI controller parameters.

Analysis results indicate that one of the major factors affecting the delay margins are the gains of PI controller and inertia of load/generator. For constant integral gain, at first the delay margin inclines upwards and then later decreases, when proportional gain increased. The delay margin inclines upwards when we increase the proportional gain of the PI controller for an interval of 0 <

$K_P \leq 0.1$ while integral gain held constant. However, increasing proportional gain beyond the $K_P > 0.1$ is decreasing the time delay margin. A small decrease in K_P gains of the controller for $K_P \leq 0{,}1$ may result in a significant increase for the delay margin. Also increasing inertia increases delay margin but Increasing damping factor causes very little increase on delay margin. For the future work, the effects of the time delays on stability in the load frequency-controlled hybrid power generation/storage system are going to be investigated with considering the gain and phase margins.

Authors' contributions

SA designed the system structure. HE carried out the experimental work, the theoretical calculations, simulations in Matlab, in collaboration with SA, and wrote up the article.

Both authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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