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# Control Applications in Modern Power Systems

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Jitendra Kumar · Manoj Tripathy · Premalata Jena  
Editors

# Control Applications in Modern Power Systems

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 Springer

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# Lyapunov Stability Analysis of Time-Delayed Load Frequency Control System with Electric Vehicles and Demand Response



A. Jawahar and K. Ramakrishnan

**Abstract** This manuscript explores the influence of time-delays on the single-area load frequency control (LFC) system stability with electric vehicles (EVs) integration in addition to the demand response (DR) control. The signal transmission through communication links in the LFC systems results in inevitable non-identical time-delays in the system feedback paths causing delay-dependent stability issues. The existence of time-delays hinders the transmission of signals among the different entities involved in the control task. This, in turn, invariably degrades the overall performance and affects the system stability. If the network induced time-delays go beyond a critical value called stable delay margin, the overall system loses stability. In this manuscript, using Lyapunov–Krasovskii functional approach, a new stability analysis is presented for ascertaining delay-dependent stability of networked load frequency control systems. The stable delay margins are obtained for different scenarios by varying the controller values of LFC controller and DR control along with participation ratios of conventional generation, electric vehicles and demand response control. The extensive simulation results are also provided to demonstrate the obtained analytical delay margin results.

**Keywords** Load frequency control systems · Electric vehicle aggregator · Demand response · Linear matrix inequality · Delay-dependent stability · Time-delays

## 1 Introduction

LFC is a mechanism employed in power systems to maintain harmony between power generation and load demand. Nowadays, open communication networks are widely used for transmission of load frequency control signals from central controller to the various sub-systems. Time-delays are the offspring of the usage of open communication networks in the LFC systems [1–3]. The time-delays, if neglected and not dealt properly can drive the system to instability. Unstable system operation is the most

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undesirable power system characteristic feature. The time-delays can show strong adverse impact on the closed loop system performance. Therefore, the maximum permissible limit of these delays (also termed as delay margin) needs to be determined for the system [4–6, 10].

EV based energy storage devices are employed for counteracting the fluctuations in the power due to intermittent nature of renewable energy resources. Generally, numerous EVs are integrated to the power system and this fleet of EVs is termed as Electric vehicle aggregator (EVA). Thus, EVA consists of thousands of EVs and act as a co-ordination center between the central control center and individual EV. The function of EVA is to obtain the control signals from the main control center and transmit the individual EV status to the main control center for necessary control action and attention. EVA can also aid in the frequency regulation apart from meeting the power requirements in the power system [7–9, 19–22].

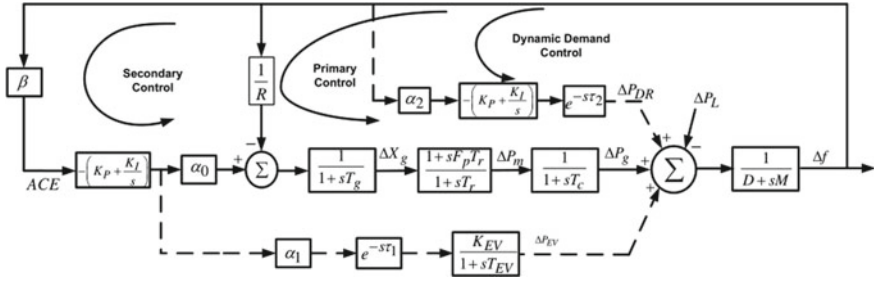
DR is the heart and soul of the evolving modern power systems which can also assist in the process of frequency regulation. The main objective of DR deployment in the power systems happens to be optimising the electricity consumption during the peak usage time and promote off-peak energy utilisation by providing monetary benefit to the consumers as well as utilities [11–15]. The EV and DR control also require communication infrastructure for signal transmission in the LFC system thereby paving a way for delays in the LFC-EV-DR system.

This manuscript presents the determination of the delay margins of the LFC-EV-DR systems with non-identical communication network time-delays in the EVA loop and DR control. In the literature, the time-delays in EVA loop and DR control are assumed to be identical and similar for assessing the delay-dependent stability of LFC systems. In practical viewpoint, the delays in the closed loop system are unique and dissimilar in nature. Using a novel Lyapunov–Krasovskii functional based approach, delay-dependent stability is established for LFC-EV-DR systems.

## 2 LFC-EV-DR System with Time-Delays

The schematic diagram of the LFC-EV-DR system is shown in Fig. 1. In the event of generation-power demand mismatch, the central controller on the basis of feedback signal from the incremental frequency variable  $\Delta f_i$  and the incremental tie-line power  $\Delta P_{tie,i}$ , initiates the control action to re-establish the balance between the generation-power demand.

The load frequency control signal is routed through communication channels along with the appropriate load sharing factors that choose the sharing of surplus/shortage load demand by the traditional generation, EVA and DR control methodologies correspondingly. In the practical situations, the delays in the EVA loop and DR control loop of a particular control area are dissimilar. However, in the existing literature, the delays in the feedback loops are considered as similar or same while analysing the system delay-dependent stability. The notations used in Fig. 1 are given in Table 1.



**Fig. 1** LFC-EV-DR system

**Table 1** Notations

Notation	Nomenclature
$\Delta P_g$	Generator power output
$\Delta P_m$	Mechanical power output
$\Delta P_{EV}$	Power output of electric vehicle aggregator
$D$	Damping coefficient
$R$	Speed regulation coefficient
$\beta$	Frequency bias factor
$F_p$	Fraction of the turbine power
$T_c$	Turbine time constant
$T_r$	Reheat turbine time constant
$T_g$	Governor time constant
$M$	Inertia constant of generator
$T_{EV}$	Time constant of electric vehicle aggregator
$K_{EV}$	Gain of electric vehicle aggregator
$K_P$	Proportional gain of PI controller
$K_I$	Integral gain of PI controller
$\alpha_0$	Participation factor of conventional generation
$\alpha_1$	Participation factor of electric vehicle aggregator
$\alpha_2$	Participation factor of DR control
$\tau_1$	Time-delay in electric vehicle aggregator
$\tau_2$	Time-delay in DR control loop
$\tau_d$	Time-delay margin

The LFC system with dissimilar time-delays in the EVA and DR control loops as shown in Fig. 1 is modeled in the following autonomous state-space analysis as follows:

$$\dot{x}(t) = Ax(t) + A_1x(t - \tau_1) + A_2x(t - \tau_2) \quad (1)$$

$$x(t) = \Phi(t), \forall t \in [-\max(\tau_1, \tau_2), 0] \quad (2)$$

where  $x(t) \in R^{6 \times 1}$  is the state vector, and  $A \in R^{6 \times 6}$ ,  $A_1 \in R^{6 \times 6}$  and  $A_2 \in R^{6 \times 6}$  are the system matrices associated with current state vector and delayed state vectors. The initial condition  $\Phi(t)$  is defined in  $t \in [-\max(\tau_1, \tau_2), 0]$ .

$$A = \begin{bmatrix} -\frac{D}{M} & \frac{1}{M} & 0 & 0 & 0 & \frac{1}{M} \\ 0 & -\frac{1}{T_c} & \frac{1}{T_c} & 0 & 0 & 0 \\ \frac{F_p \alpha_0 K_p \beta}{T_g} - \frac{F_p}{RT_g} & \frac{F_p}{RT_g} & 0 & -\frac{1}{T_r} - \frac{F_p}{T_s} + \frac{1}{T_r} & \frac{F_p \alpha_0 K_i}{T_g} & 0 \\ -\frac{\alpha_0 K_p \beta}{T_g} - \frac{1}{RT_g} & 0 & 0 & -\frac{1}{T_g} & -\frac{\alpha_0 K_i}{T_g} & 0 \\ \beta & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{EV}} \end{bmatrix}$$

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{K_{EV} \alpha_1 K_p \beta}{T_{EV}} & 0 & 0 & 0 & -\frac{K_{EV} \alpha_1 K_i}{T_{EV}} & 0 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} -\frac{K_p \alpha_2}{M} & 0 & 0 & 0 & 0 & -\frac{K_i \alpha_2}{M} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

### 3 Stability Criterion

For deriving the stability criterion for assessing the delay-dependent-stability of system (1) subjected to (2), following lemmas are required.

**Lemma 1: Jensen Integral Inequality** [16]: For any positive symmetric constant matrix  $M \in R^{n \times n}$ , scalars  $r_1 < r_2$ , a vector valued function  $\omega : [r_1, r_2] \rightarrow R^n$  such that the integrations concerned are well defined, then the inequality (3) holds.

$$\left( \int_{r_1}^{r_2} \omega(s) ds \right)^T M \left( \int_{r_1}^{r_2} \omega(s) ds \right) \leq (r_2 - r_1) \int_{r_1}^{r_2} \omega^T(s) M \omega(s) ds \quad (3)$$

**Lemma 2: Wirtinger Inequality** [17]: For given symmetric positive definite matrix  $R$ , and for any differentiable signal  $\omega$  in  $[a, b] \rightarrow R^n$ , then the equality (4) holds.

$$\int_b^a \dot{\omega}^T(u) R \dot{\omega}(u) du \geq \frac{1}{b-a} \begin{bmatrix} \omega(b) \\ \omega(a) \\ \frac{1}{b-a} \int_a^b \omega(u) du \end{bmatrix}^T \begin{bmatrix} 4R & 2R & -6R \\ * & 4R & -6R \\ * & * & 12R \end{bmatrix} \begin{bmatrix} \omega(b) \\ \omega(a) \\ \frac{1}{b-a} \int_a^b \omega(u) du \end{bmatrix} \quad (4)$$

The proposed stability criterion for the system in (1) is given in the form of the following theorem:

**Theorem 1** The system (1) with time-delays  $\tau_1$  and  $\tau_2$  is asymptotically stable in the sense of Lyapunov, if there exists real symmetric positive definite matrices  $P_{11}, S_1, S_2, R_1, R_2$  and  $R_3$ ; symmetric matrices  $P_{22}$  and  $P_{33}$ ; free matrices  $P_{12}, P_{13}$  and  $P_{23}$  of appropriate dimensions such that the following linear matrix inequalities (LMIs) hold:

$$\Pi_0 > 0 \quad (5)$$

$$\begin{bmatrix} \sum_{k=1}^5 \Pi_k & \bar{A}^T U_1 & \bar{A}^T U_2 \\ * & -U_1 & 0 \\ * & * & -U_2 \end{bmatrix} < 0 \quad (6)$$

where

$$\Pi_0 = P + \text{diag}([0, \tau_1^{-1} S_1, \tau_2^{-1} S_2]),$$

$$\Pi_1 = \Phi_1^T P \Phi_2 + (\Phi_1^T P \Phi_2)^T,$$

$$\Pi_2 = \text{diag}([S_1 + S_2, -S_1, -S_2, 0, 0]),$$

$$\Pi_3 = \begin{bmatrix} -\frac{4}{\tau_1} R_1 & -\frac{2}{\tau_1} R_1 & 0 & \frac{6}{\tau_1} R_1 & 0 \\ * & -\frac{4}{\tau_1} R_1 & 0 & \frac{6}{\tau_1} R_1 & 0 \\ * & * & 0 & 0 & 0 \\ * & * & * & -\frac{12}{\tau_1} R_1 & 0 \\ * & * & * & * & 0 \end{bmatrix},$$

$$\Pi_4 = \begin{bmatrix} -\frac{4}{\tau_2} R_2 & 0 & -\frac{2}{\tau_2} R_2 & 0 & \frac{6}{\tau_2} R_2 \\ * & 0 & 0 & 0 & 0 \\ * & * & -\frac{4}{\tau_2} R_2 & 0 & \frac{6}{\tau_2} R_2 \\ * & * & * & 0 & 0 \\ * & * & * & * & -\frac{12}{\tau_2} R_2 \end{bmatrix},$$

$$\Pi_5 = [0 \ I \ -I \ 0 \ 0]^T (-R_{12}) [0 \ I \ -I \ 0 \ 0].$$

with

$$\begin{aligned}
P &= \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ * & P_{21} & P_{22} \\ * & * & P_{33} \end{bmatrix}, \\
\Phi_1 &= \begin{bmatrix} I & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \tau_1 & 0 \\ 0 & 0 & 0 & 0 & \tau_2 \end{bmatrix}^T, \\
\Phi_2 &= \begin{bmatrix} A & A_1 & A_2 & 0 & 0 \\ I & -I & 0 & 0 & 0 \\ I & 0 & -I & 0 & 0 \end{bmatrix}, \\
\bar{A} &= [A \ A_1 \ A_2 \ 0 \ 0], \\
U_1 &= \tau_1 R_1 + \tau_2 R_2, \\
U_2 &= (\tau_2 - \tau_1)^2 R_{12}.
\end{aligned}$$

**Proof** The LK functional  $V(x(t)) = \sum_{i=1}^4 V_i(x(t))$  with

$$V_1(x(t)) = \Xi^T(t) P \Xi(t) \quad (7)$$

$$V_2(x(t)) = \sum_{i=1}^2 \int_{t-\tau_i}^t x^T(s) S_i x(s) ds \quad (8)$$

$$V_3(x(t)) = \sum_{i=1}^2 \int_{-\tau_i}^0 \int_{t+\theta}^t \dot{x}^T(s) R_i \dot{x}(s) ds d\theta \quad (9)$$

$$V_4(x(t)) = (\tau_2 - \tau_1) \int_{-\tau_2}^{-\tau_1} \int_{t+\theta}^t \dot{x}^T(s) R_3 \dot{x}(s) ds d\theta \quad (10)$$

with  $\Xi(t) = \left[ x^T(t) \int_{t-\tau_1}^t x^T(s) ds \int_{t-\tau_2}^t x^T(s) ds \right]^T$ .

The following conditions hold, by (3):

$$\int_{t-\tau_1}^t x^T(s) S_1 x(s) ds \geq \left[ \int_{t-\tau_1}^t x(s) ds \right]^T \left( \frac{S_1}{\tau_1} \right) \left[ \int_{t-\tau_1}^t x(s) ds \right] \quad (11)$$

$$\int_{t-\tau_2}^t x^T(s) S_2 x(s) ds \geq \left[ \int_{t-\tau_2}^t x(s) ds \right]^T \left( \frac{S_2}{\tau_2} \right) \left[ \int_{t-\tau_2}^t x(s) ds \right] \quad (12)$$

By using the above Eqs. (11) and (12), one can readily obtain a lower bound for  $V(x(t))$  as follows:

$$V(x(t)) \geq \Xi(t)^T \Pi_0 \Xi(t) + V_3(x(t)) + V_4(x(t)) \quad (13)$$

The positive definiteness of  $S_i$ ,  $R_j$ ; and  $\Pi_0 > 0$  implies positive definiteness of  $V(x(t))$ .

The time-derivative of  $V_1(x(t))$  is given by

$$\dot{V}_1(x(t)) = 2\Xi^T(t)P\dot{\Xi}(t) \quad (14)$$

which can be rewritten as

$$\dot{V}_1(x(t)) = \delta^T(t) \Pi_1 \delta(t) \quad (15)$$

where  $\delta(t) = \left[ x^T(t) \ x^T(t - \tau_1) \ x^T(t - \tau_2) \ \frac{1}{\tau_1} \int_{t-\tau_1}^t x^T(s) ds \ \frac{1}{\tau_2} \int_{t-\tau_2}^t x^T(s) ds \right]^T$  is an augmented state vector.

The time-derivative of  $V_2(x(t))$  is given by

$$\dot{V}_2(x(t)) = x^T(t)(S_1 + S_2)x(t) - \sum_{i=1}^2 x^T(t - \tau_i) S_i x(t - \tau_i) \quad (16)$$

The Eq. (16), in terms of  $\delta(t)$ , is expressed as follows:

$$\dot{V}_2(x(t)) = \delta^T(t) \Pi_2 \delta(t) \quad (17)$$

The time-derivative of the  $V_3(x(t))$  is given by

$$\dot{V}_3(x(t)) = \dot{x}^T(t) U_1 \dot{x}(t) - \int_{t-\tau_1}^t \dot{x}^T(s) R_1 \dot{x}(s) ds - \int_{t-\tau_2}^t \dot{x}^T(s) R_2 \dot{x}(s) ds \quad (18)$$

Now, by using Wirtinger inequality, the Eq. (18) is expressed as follows:

$$\dot{V}_3(x(t)) \leq \delta^T(t) \left( \bar{A}^T U_1 \bar{A} \right) \delta(t) + \delta^T(t) \Pi_3 \delta(t) + \delta^T(t) \Pi_4 \delta(t) \quad (19)$$

The time-derivative of  $V_4(x(t))$  is given by

$$\dot{V}_4(x(t)) = \dot{x}^T(t) U_2 \dot{x}(t) - (\tau_2 - \tau_1) \int_{t-\tau_2}^{t-\tau_1} \dot{x}^T(s) R_{12} \dot{x}(s) ds \quad (20)$$

Now, (20) is expressed as an inequality using (3) as:

$$\dot{V}_4(x(t)) \leq \delta^T(t) \left( \bar{A}^T U_2 \bar{A} \right) \delta(t) + \delta^T(t) \Pi_5 \delta(t) \quad (21)$$

By combining the  $\dot{V}_i(x(t))$ ,  $i = 1$  to  $4$ , the following condition was obtained:

$$\dot{V}(x(t)) = \sum_{i=1}^4 \dot{V}_i(x(t)) \leq \delta^T(t) \left[ \sum_{k=1}^5 \Pi_k + \bar{A}^T (U_1 + U_2) \bar{A} \right] \delta(t). \quad (22)$$

Now, by Schur Complement, if the inequality conditions (3) and (4) hold simultaneously, then there exists a sufficiently small scalar  $\alpha > 0$  such that  $\dot{V}(x(t)) \leq -\alpha \|x(t)\|^2$ , which, in turn, implies that the LFC systems described by (1) are asymptotically stable in the sense of Lyapunov [18]. By solving the stability criterion, the delay margin values for the LFC-EV-DR systems are obtained.

## 4 Results

The system parameters are given in Table 2. The controllers in secondary frequency loop and DR loop are of PI type with same controller gains ( $K_P$  and  $K_I$ ). The stable delay margin values obtained using the Lyapunov stability criterion are listed in Tables 3, 4, 5, 6 and 7 for different  $K_P$ ,  $K_I$  values. The time-delays are given as  $\tau_d = \sqrt{\tau_1^2 + \tau_2^2}$  and  $\theta = \tan^{-1} \left( \frac{\tau_2}{\tau_1} \right)$ .

For the stable delay margin computation, the  $K_P$  is varied from 0.4 to 1.0 in steps of 0.2, and the  $K_I$  is set as 0.6 and 0.8. The Tables 3 and 4 present the delay margin values provided by the proposed stability criterion for various values of  $K_P$  and  $K_I$  of LFC controller with participation factor  $\alpha_0 = 0.8$ ,  $\alpha_1 = 0.1$  and  $\alpha_2 = 0.1$ . The Tables 5 and 6 show the delay margin values for different controller gains with participation factor  $\alpha_0 = 0.7$ ,  $\alpha_1 = 0.2$  and  $\alpha_2 = 0.1$ . The Tables 7 and 8 present

**Table 2** Parameters under study

Notation	Value
$M$	8.8
$D$	1
$F_p$	1/6
$R$	1/11
$\beta$	21
$T_g$	0.2
$T_c$	0.3
$T_r$	12
$T_{EV}$	0.1
$K_{EV}$	1

**Table 3** Delay margin results for  $K_I = 0.6$ ,  $\alpha_0 = 0.8$ ,  $\alpha_1 = 0.1$  and  $\alpha_2 = 0.1$ 

$\theta$	$K_p = 0.4$	$K_p = 0.6$	$K_p = 0.8$	$K_p = 1$
5	1.520	2.154	2.708	3.293
10	1.546	2.187	2.742	3.310
20	1.633	2.295	2.843	3.344
30	1.781	2.470	3.007	3.438
40	2.015	2.747	3.278	3.659
45	2.185	2.953	3.490	3.847
50	2.366	3.183	3.737	4.093
60	2.937	3.880	4.526	5.021
70	4.051	5.388	6.538	7.340
80	7.562	10.612	12.877	14.458
85	15.068	21.144	25.657	28.806

the delay margin values for different controller gains with participation factor  $\alpha_0 = 0.7$ ,  $\alpha_1 = 0.1$  and  $\alpha_2 = 0.2$ . The results illustrate that the LFC-EV-DR system stability is enhanced when a DR control loop is added while the delay margin is decreased with the higher EV participation.

For the purpose of validation of the analytical results, simulation studies are conducted, where the system is subjected to a unit step load perturbation of  $\Delta P_D = 0.1 pu$  at  $t = 0$ , and the incremental frequency variable  $\Delta f(t)$  response is observed for  $t > 0$ . For  $K_p = 0.6$  and  $K_I = 0.8$ , with  $\alpha_0 = 0.7$ ,  $\alpha_1 = 0.2$  and  $\alpha_2 = 0.1$ , from Table 5, the stable delay margin obtained is  $\tau_d = 2.339$  for  $\theta = 50^\circ$ . The LFC-EV-DR system is stable upto  $\tau_d = 2.339$  as per the presented stability criterion. The incremental frequency variable exhibits an asymptotically stable response for  $\tau_d =$

**Table 4** Delay margin results for  $K_I = 0.8$ ,  $\alpha_0 = 0.8$ ,  $\alpha_1 = 0.1$  and  $\alpha_2 = 0.1$ 

$\theta$	$K_p = 0.4$	$K_p = 0.6$	$K_p = 0.8$	$K_p = 1$
5	0.864	1.353	1.756	2.081
10	0.881	1.378	1.786	2.112
20	0.938	1.460	1.879	2.202
30	1.034	1.595	2.026	2.341
40	1.188	1.805	2.255	2.564
45	1.298	1.957	2.426	2.736
50	1.415	2.109	2.607	2.927
60	1.799	2.592	3.152	3.515
70	2.507	3.529	4.278	4.948
80	4.256	6.504	8.397	9.746
85	8.052	12.959	16.732	19.418

**Table 5** Delay margin results for  $K_I = 0.6$ ,  $\alpha_0 = 0.7$ ,  $\alpha_1 = 0.2$  and  $\alpha_2 = 0.1$ 

$\theta$	$K_p = 0.4$	$K_p = 0.6$	$K_p = 0.8$	$K_p = 1$
5	1.128	1.437	1.609	1.665
10	1.147	1.460	1.633	1.688
20	1.213	1.540	1.716	1.767
30	1.327	1.674	1.853	1.897
40	1.510	1.888	2.071	2.104
45	1.642	2.042	2.231	2.257
50	1.781	2.212	2.412	2.435
60	2.241	2.735	2.960	2.975
70	3.118	3.774	4.111	4.212
80	5.663	7.267	8.098	8.297
85	11.284	14.48	16.136	16.532

**Table 6** Delay margin results for  $K_I = 0.8$ ,  $\alpha_0 = 0.7$ ,  $\alpha_1 = 0.2$  and  $\alpha_2 = 0.1$ 

$\theta$	$K_p=0.4$	$K_p=0.6$	$K_p=0.8$	$K_p=1$
5	0.743	1.020	1.209	1.313
10	0.758	1.039	1.230	1.335
20	0.806	1.102	1.301	1.407
30	0.889	1.209	1.417	1.522
40	1.021	1.376	1.598	1.701
45	1.116	1.497	1.729	1.832
50	1.218	1.616	1.865	1.973
60	1.552	2.013	2.285	2.398
70	2.168	2.762	3.114	3.265
80	3.695	4.955	5.909	6.391
85	6.976	9.873	11.773	12.735

2.3, marginally stable response for  $\tau_d = 2.339$  and unstable response for  $\tau_d = 2.4$  as illustrated in Fig. 2. Therefore, the effectiveness of the analytical delay bounds is validated through the simulation results.

## 5 Conclusions

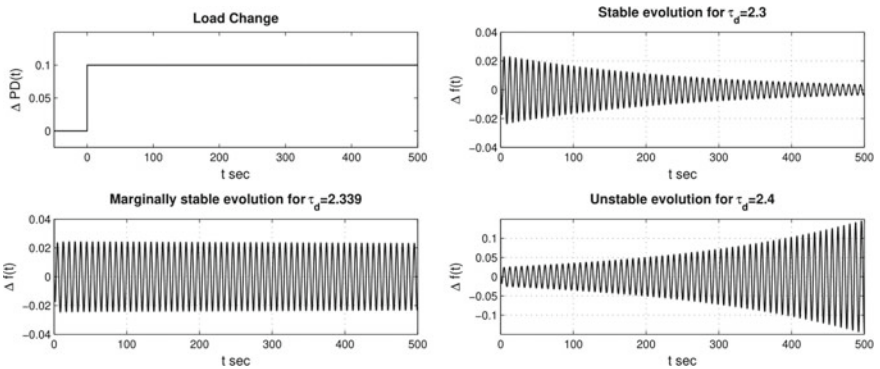
This study presents the comprehensive delay-dependent stability analysis of a class of networked single-area LFC systems with communication delays. The electric vehicles and demand response are integrated to the LFC systems. This network architecture introduces two non-identical time-delays in the system feedback paths.

**Table 7** Delay margin results for  $K_I = 0.6, \alpha_0 = 0.7, \alpha_1 = 0.1$  and  $\alpha_2 = 0.2$

$\theta$	$K_p=0.4$	$K_p=0.6$	$K_p=0.8$	$K_p=1$
5	1.721	2.393	3.019	3.830
10	1.760	2.438	3.054	3.772
20	1.872	2.551	3.109	3.598
30	2.041	2.704	3.190	3.527
40	2.294	2.944	3.367	3.612
45	2.479	3.136	3.536	3.739
50	2.639	3.322	3.718	3.906
60	3.156	3.889	4.324	4.571
70	4.156	5.122	6.055	6.624
80	7.356	10.051	11.926	13.047
85	14.656	20.026	23.761	25.996

**Table 8** Delay margin results for  $K_I = 0.8, \alpha_0 = 0.7, \alpha_1 = 0.1$  and  $\alpha_2 = 0.2$

$\theta$	$K_p=0.4$	$K_p=0.6$	$K_p=0.8$	$K_p=1$
5	1.018	1.531	1.971	2.349
10	1.047	1.572	2.016	2.388
20	1.133	1.681	2.119	2.456
30	1.268	1.834	2.249	2.536
40	1.470	2.055	2.446	2.688
45	1.612	2.217	2.604	2.828
50	1.715	<b>2.339</b>	2.743	2.967
60	2.115	2.752	3.171	3.411
70	2.791	3.558	4.077	4.540
80	4.300	6.072	7.776	8.942
85	7.603	12.099	15.494	17.817



**Fig. 2** Evolution of  $\Delta f(t)$  for various values of delay

Such time-delays in the feedback loop affect the system dynamic performance. Stable delay margins are computed for different subsets of control parameters and load sharing factors. The proposed stability criterion will be used for assessing the LFC-EV-DR system delay-dependent stability with time-varying delays will be explored in future.

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# Coordinated Control of PHEVs and DEGs for Frequency Control of Two Area Hybrid Microgrid: An Effective Utilization of PID Controller for Renewable Applications



Anil Annamraju, Sheba Rani, SreenivasaRatnam, and Dileep Mathi

**Abstract** Present Microgrid (MG) faces uncertainty from Renewable Energy Sources (RES) and loads which cause hefty frequency deviations. Apart from the control strategies for Diesel Engine Generators (DEGs) and Energy Storage Systems (ESSs), MG requires an effective and intelligent coordinate strategy between DEG and ESSs for MG frequency control. In response to this, present paper addresses a coordinated control strategy between Plug-in Hybrid Electric Vehicles (PHEVs) and DEGs for MG frequency control under different operating scenarios. The proposed strategy is based on Cascade PD-PI controller whose gains are tuned using Sparrow Search Optimization (SSO) algorithm. Proposed controller is tested on Two-Area MG Simulink model. MG dynamic responses are obtained by considering load and RES changes. A comparative assessment of the proposed approach with SSO and BES optimized PID controller was performed. Simulation results confirm that the proposed controller enhances frequency dynamics of MG significantly. Moreover, the proposed Cascade PD-PI approach is robust to MG and PHEV parametric uncertainties as compared to PID controller.

**Keywords** Frequency control · PHEVs · Primary and secondary loops · Cascade PD-PI controller · Coordinated control · Sparrow search algorithm

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## 1 Introduction

Production of electricity by using fossil fuels caused a serious threat to environment due to emission of toxic gases that led to global warming. Fossil fuels reserve has reached the edge of depletion and could not meet the continuously increasing energy demand. Despite today's technological advancements electrical energy is still inaccessible for low populated areas rural regions and islands due to geographical and monetary constraints. A need to address all these issues arose which necessitated lot of research and development. Microgrid (MG) is associated with an integrated operation of multiple renewable energy resources and energy storage systems (ESSs). MG provides an efficient solution for aforementioned problems of rural electrification and extinction of fossil fuels [1].

A method for Load frequency control (LFC) involves employing a traditional controller to introduce a restorative signal at the governor summing point [2, 3]. Factors such as low system inertia and non-linear behavior of source and load affect the performance of controller thus resulting in frequency deviations beyond admissible limits. The conventional controller fails to exhibit adequate performance in all possible operating scenarios [4]. To overcome this problem several authors proposed Artificial Intelligent (AI) technique based PID controllers for LFC problem of hybrid MG [5–9]. PI/PID controllers whose gains were determined using GA were employed for compensating load frequency deviations in an MG [5]. Social Spider Optimization (SSO) was adopted for tuning of PID controller to achieve coordinated control in the event of sudden disturbances occurring in MG [6]. A novel algorithm by name quasi-oppositional harmony search algorithm (QOHS) was introduced for optimization of controller gains when frequency deviations occur at generation side and load side [7]. Another method for LFC was presented using Grass Hopper Optimizer (GOA) based PID controller operating in coordination with Redox Flow Batteries [8]. A load frequency controller tuned by Grey Wolf Optimizer (GWO) was introduced for a standalone Two-Area hybrid MG system [9].

Though AI based PID controllers are providing an acceptable performance in wide range of operating conditions, the main drawback with these controllers is improper arbitrates between derivative and integral parts which leads to under performance than its capability. To overcome this problem, in literature, authors recommended various multi-stage PID controllers [10–12]. In [10] authors proposed hybrid optimization based multi-stage PID controller. In [11] authors suggested Slap Swarm Algorithm (SSA) based Cascade PI-PD controller, in [12] authors proposed a Chaotic Crow Search algorithm based PD-tilt PI controller. From the detailed study of these papers, the aforementioned controllers provided a guaranteed improved performance than PID controllers. In continuation to this, in present paper PD controller in primary control and PI controller in secondary control were proposed. Gains of Cascade PD-PI controller are optimized using Sparrow Search Optimization (SSO) algorithm. According to No Free Lunch theorem, no single meta-heuristic technique is suitable to optimize all engineering problems and improvement always persists. For this test system and operating conditions, SSO gave optimal performance than several recent algorithms. The key contributions of this paper are listed as follows.

## 2 Two-Area MG Modeling

Figure 1 illustrates the mathematical model of Two-Area MG. It depicts the linearized model of autonomous Two-Area hybrid MG which consists of Diesel Engine Generator (DEG), Wind Turbine Generator (WTG), Photo Voltaic (PV) array and Plug-in Hybrid Electric Vehicles (PHEVs) [4, 13]. Modeling of these components is presented in subsequent sections. Parameters required for simulation are available in [8, 13].

### 2.1 Modeling of DEG

Simulink model of DEG is shown in Fig. 2. Taking RES output into consideration DEG will supply the power that is deficit to the load. Depending on the command signal ( $U_c$ ) obtained from the controller; speed governor will adjust the position of the valve. Change in the valve position is denoted as  $\Delta X$ .

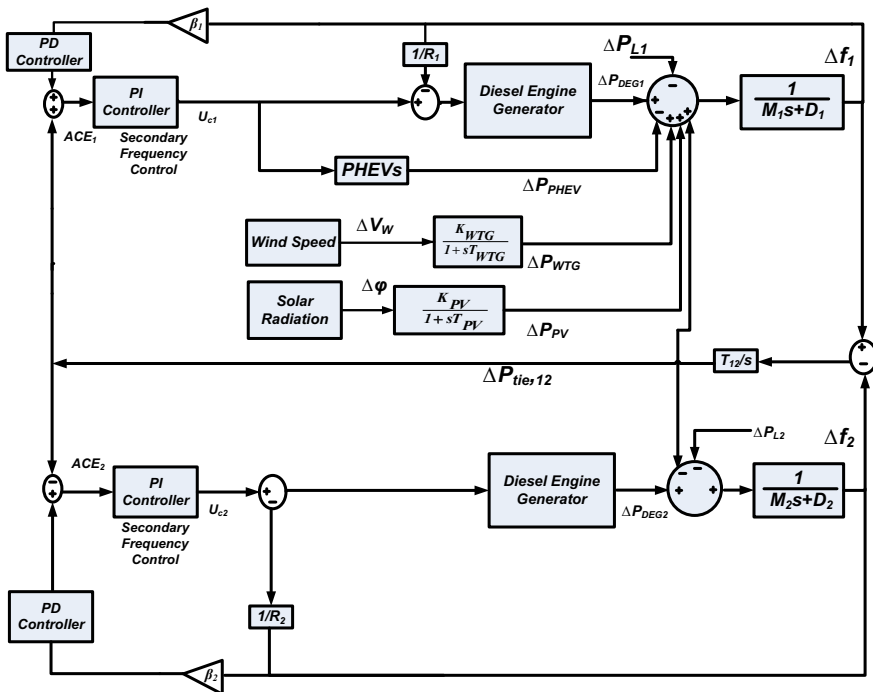


Fig. 1 Mathematical model of Two-Area Microgrid

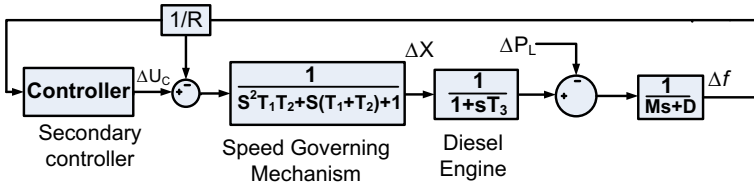


Fig. 2 Mathematical model of DEG

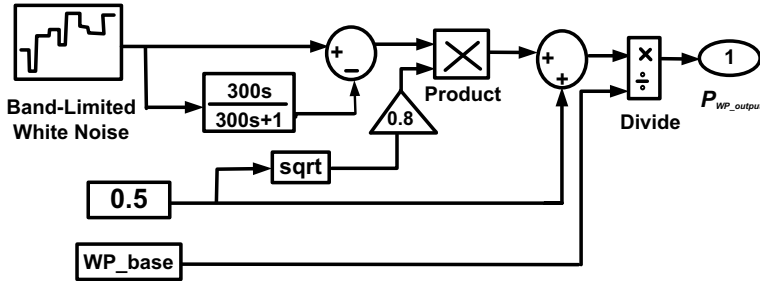


Fig. 3 Mathematical model for wind velocity pattern generation

### 2.2 Modeling of WTG

Output power of WTG is a function of speed of the wind. Due to the inconsistent nature of the wind, its speed keeps varying randomly. Mechanical power output of the windmill ( $P_{wp}$ ) is expressed as [4]:

$$P_{wp} = 0.5 \rho A V_w^3 C_p(\beta, \lambda) \tag{1}$$

Linear model of WTG can be expressed as [4]:

$$TF_{WTG} = \frac{\Delta P_{WTG}}{P_{WP\_output}} = \frac{K_{WTG}}{1 + ST_{WTG}} \tag{2}$$

Mathematical modeling for generating wind output power fluctuations is given in Fig. 3.

### 2.3 Modeling of PV Array

A PV array is a collection of many PV modules connected together in both series and parallel combinations. Voltage and current ratings of the PV array is determined by the number of PV modules arranged in series-parallel combinational circuits.

Changes in load current and solar radiation are the factors that regulate the output power of PV array. In this research work in order to study frequency regulation it is assumed that PV output power varies only with solar radiation.

First-order model of the PV system can be expressed as [4]:

$$TF_{PV} = \frac{\Delta P_{PV}}{\Delta \varphi} = \frac{K_{PV}}{1 + sT_{PV}} \quad (3)$$

WTG data and PV power data used in this work are available in [4].

## 2.4 Mathematical Model of PHEVs

DEG usually delivers the electrical energy that is deficit to the demand side thus causing a balance between generation and the load. However DEG exhibits a very slow response in the event of frequency oscillations due to its large time constants. This makes it less effective when sudden frequency variations occur in RES output power and load [14]. To withstand these deviations in frequency regulation of MG with DEG and suitable distributed storage systems have been proposed. Recent studies revealed the significance and suitability of PHEVs in RES integrated systems. As compared to other existing technologies PHEVs have simple modular structure, slow discharge rate, fast-acting capability and distributed availability. Figure 4 illustrates the mathematical model of PHEV aggregator for LFC studies [14]. Instantaneous change in PHEV power can be expressed as follows [14]: (Fig. 5)

$$\Delta P_{PHEV,i} = \begin{cases} K_{EV,i} \Delta f; & |K_{EV,i} \Delta f| \leq P_{max} \\ P_{max}; & K_{EV,i} \Delta f > P_{max} \\ -P_{max}; & K_{EV,i} \Delta f < -P_{max} \end{cases} \quad (4)$$

$$\Delta P_{PHEV,AG} = N_{EV} * \Delta P_{PHEV,i} \quad (5)$$

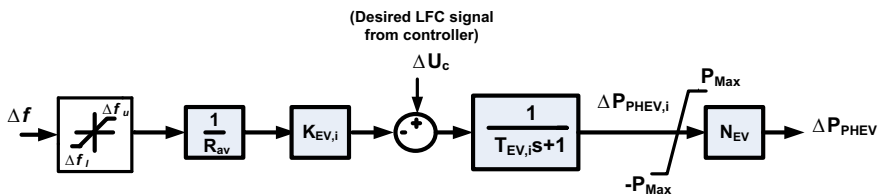


Fig. 4 PHEV aggregator model for frequency control studies