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Distributed Secondary Control for Islanded Microgrids Considering Small and Large Communication Delays

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Abstract

A distributed control of a Microgrid (MG) depends on the Communication Network (CN) for the exchange of information among the Distributed Generators (DGs). Most of the existing control schemes consider ideal communication among the DGs however, in practical systems, delays are inherited that can affect the dynamic performance and even destabilize an MG. Therefore, in this research work, a distributed secondary controller for an islanded MG is designed considering communication delays. Sufficient delay-independent conditions for robust stability of the buffer free distributed averaging proportional integral control scheme are proposed. Both small and large time varying communication delays are analysed using Lyapunov Krasovskii and Lyapunov Razumikhin's approach. A sensitivity analysis is performed to demonstrate the system's stability. Finally, the efficacy of the controller is demonstrated through simulation studies.

Keywords: *distributed control, islanded microgrid, secondary control, communication delays, hierarchical control*

I. Introduction

Microgrid has gained significant interest in the past decade due to its prosumer-friendly architecture, scalable nature, and integration of Renewable Energy Resources (RES). However, due to low or zero inertia and intermittent power generation of RESs, numerous issues arise, such as voltage fluctuations, frequency deviation, system instability, supply-demand imbalances, etc. [1]. Due to these uncertainties, an MG is operated under highly stressed conditions; thus, a robust control strategy is required to guarantee an efficient and reliable operation [2].

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The control of an MG is generally practiced in hierarchical manner that is composed of three levels, i.e. primary, secondary, and tertiary control levels. A primary control is a basic level having a minimum decision time step and is concerned with the MG stability [3]. The main objective of Secondary Control (SC) level is to eliminate the aforementioned deviations in voltages and frequencies along with some other control objectives such as reactive power-sharing, grid synchronization, and harmonic compensation, etc. are [4]. The final level of the hierarchy is a tertiary control and is concerned with global economic optimization depending on energy prices and current markets [5]. Moreover, this hierarchical control structure is usually implemented using centralized, decentralized, and distributed control architecture [6, 7]. Due to numerous advantages of the distributed structure compared to others in this manuscript a main focus is given to the SC of an MG implemented in distributed architecture while considering communication delays.

To cope with this issue numerous researchers have developed different control strategies. For instance, the authors in [8, 9] study the effect of fixed delays on the performance of SC scheme. Similarly, in [10], a stochastic consensus based cooperative controller is presented for voltage and frequency regulation under noise disturbance and communication delays. These studies [8-10] only focus on the fact that all the links have same delay however, in practical, the communication delays are arbitrary and time varying rather than fix. Hence, to cope with this limitation, the authors in [11, 12] uses a master-slave distributed secondary control scheme to develop the stability conditions for TVDs along with switching topology. However, this master-slave architecture introduces an additional uncertainty that the failure of the leader may lead towards the instability of the system [13]. Similarly, the authors in [14] proposed a distributed finite time control schemes for frequency regulation and optimal power sharing with TVDs by adjusting graph gains. This method is only feasible for small varying delays and need to optimize the communication topology in advance. Moreover, in this research, multiple leaders are considered that may lead to computational complexity. In [16], the author proposed an accurate consensus based distributed averaging control with TVDs, however, not considering the switching topology and the fast TVDs in the communication network. Another consensus-based delay tolerant distributed control scheme is presented in [17], however, the author is more tilted towards equal power sharing and tracking of varying averaging loads with finite time convergence.

The State-of-the-art work discussed above usually used a buffer based control schemes are discussed to compensate the delays in the communication network. However, the buffer itself requires more power, storage, memory, and computation to operate normally [18]. Moreover, the buffer memory may become insufficient, in case, the systems scale up or the number of participants increase. Therefore, using a buffer-based controller to minimize the time delay uncertainties may not be feasible. Hence, based on the above discussion the major contributions of this work are presented below as:

- A delay independent secondary control scheme for an islanded MG subjected to small and large varying communication delays is proposed.
- The distributed controllers presented in [12, 14-17] are delay dependent i.e. an upper bound for the delays in the communication channels. These methods require a compensation scheme (usually buffers) to minimize the deviations. The buffer-based control schemes require more power, storage, and computation to operate, which is not desirable. Hence, our proposed method avoids the use of any compensation scheme.
- A proposed controller with time varying communication delays is implemented in a distributed manner thus enabling the PnP functionality. Moreover, the proposed control scheme shows robustness against the time-varying communication delays and load variations.

The remaining parts of the paper are arranged as follows. The preliminaries, cyber-physical model of an MG under consideration, the hierarchical control structure is discussed in Section 2. An SC scheme for frequency regulation and active power sharing is presented in Section 3. A distributed controller for voltage regulation and reactive power sharing is discussed in Section 4. The performance of the proposed control scheme is validated and results are explained in section 5. The concluding remarks and the future research direction are discussed in section 6.

II. Preliminaries

In this section, a detailed discussion is carried out regarding physical electrical network and cyber network.

A. *Physical System*

An MG with n number of buses that can either be DGs (intermittent and dispatchable) or loads (controllable and uncontrollable) is considered in this research work. Every DG is an MG consists of a DC source, Inductance-Capacitance-Inductance (LCL) filter, and inverter and it is considered that k^{th}-DG and l^{th}-DG are connected with each other through inductive lines (have a reactance = X_{kl}). Thus, the active and reactive power injected into a system are given as [4]:

$$P_k = \sum_{l=1}^{n} \frac{E_k E_l}{X_{kl}} \sin(\theta_{kl}) \tag{1a}$$

$$Q_k = -\sum_{l=1}^{n} \frac{E_k E_l}{X_{kl}} \cos(\theta_{kl}) + \frac{E_k^2}{X_k} \tag{1b}$$

where, E_k (respectively θ_k) and E_l (respectively θ_l) represents the voltage magnitude (respectively phase angle) of k^{th}-DG and l^{th}-DG respectively; and $X_k = 1 \Big/ \left(\sum_{l=1}^{n} \left(1 / X_{kl} \right) \right)$.

B. *Cyber System*

A communication network between the DGs is presented by graph theory and is modelled by using a digraph. However, before discussing the details of graph theory there are some notations that are needed to be explained. Let a set of real numbers is denoted by ¡ , hence, the notation $¡ < 0$ presents a set $\{x \mid x \in ¡\} \mid x < 0$, $¡ > 0$ defines a set $\{x \mid x \in ¡\} \mid x > 0$, and $¡ \geq 0$ denotes a set $\{x \mid x \in ¡\} \mid x \geq 0$. Let a null vector is denoted by 0_N, while 1_N indicates a vector having all entries are one i.e. $1_N=(1,1...,1)^N \in ¥$. Let G represent an undirected connected graph and $G = (¥, E)$, where, ¥ defines the set of nodes i.e., $¥ = \{1,.......n\}$, and $E = [¥]^2$ as E defines the set of edges of the undirected connected graph G i.e., $E = \{e_1,........,e_m\}$. In the present context,

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each node is considered as a power unit. The matrix $A = \mathbb{R}^{|N||N|}$ represents an adjacency matrix of the graph G, consisting of elements $a_{ij} = a_{ji} = 1$ if and only if an edge exists between the node *i* and its neighbor *j* and vice versa, else $a_{ij} = 0$. Also, the degree of the ith node is defined as $D_i = \sum_{i,j \in |N|} a_{ij}$, where $i \neq j$. The Laplacian matrix $\mathbb{L}$ of the graphG is defined as $\mathbb{L} = D - A$, where, $D = diag(D_i) \in \mathbb{R}^{|N||N|}$. The order of nodes is arranged in a such a way that there exists a path called an edge between the node *i* and its respective neighboring node *j*. If a path exists from node *i* to node *j*, the graph is considered to be connected. If G is connected, then $\mathbb{L}$ is a positive semidefinite matrix with zero eigenvalue. The corresponding right eigenvector to a zero eigenvalue is 1_n, i.e., $\mathbb{L}1_n = 0_n$ [19].

C. Hierarchal Control Structure

The control of an MG is generally practiced in hierarchical manner that composed of three levels as discussed above. However, there is another control level referred to as a zero control level and is applied at the lowest level. A zero control level is composed of current, voltage, and virtual impedance loops. The inner current and outer voltage loops are controlled in a decoupled manner therefore the dynamic speed of current loop is 5-20 times faster than the voltage loop. A comprehensive review of different controllers used in these inner loops can be found in [20]. In this paper, a Proportional Resonant controller discussed in [20] is used in these loops due to its high tracking capability (sinusoidal references) and dynamic response. Furthermore, to make an MG mainly inductive a virtual impedance loop is also used in the zero level [17].

III. Distributed Frequency Regulation and Active Power Sharing Controller

A Distributed Averaging Proportional Integral (DAPI) controller for frequency regulation and active power sharing can be given as:

$$\omega_k = \omega_{ref} - m_k P_k + u_k \quad (2a)$$

$$\frac{du_k}{dt} = K_f \left[\left(\sum_{l=1}^{n} a_{kl}(u_l - u_k) \right) + (\omega_{ref} - \omega_k) \right] \quad (2b)$$

where ω_k is the measured angular frequency of the k^{th}-DG (*k* = 1, 2,………, *n*); ω_{ref} is the angular grid frequency; m_k is an active power-angular frequency ($P - \omega$) droop coefficients and is given as $m_k = \Delta\omega_k / P_{k\max}$; u_k is the SC variable; K_f is the designed SC positive gain; $a_{kl} = 1$, if a communication-link among k^{th}-DG and l^{th}-DG exists, otherwise, $a_{kl} = 0$. An adjacency matrix for the frequency regulation and active power sharing is presented as $A = \{a_{kl}\}$. A schematic of distributed control structure is shown in Fig. 1.

From 2(b), it can be observed that it consists of two parts i.e. active power sharing and frequency restoration. In the active power sharing part, the communication among the DGs is performed through sparse communication network. Thus, in case of any communication delay, a DG will receive a delayed information from its neighbour that can affect the performance of an MG. However, in the frequency error correction part, a constant reference is provided to the controller that eliminates the need of communication for frequency error correction. Based on this, the part where communication between the DGs exists (active power sharing) is considered only while the frequency regulation term is ignored, thus 2(b) can be written as:

$$\frac{du_k}{dt} = \left[\sum_{l=1}^{n} a_{kl}(u_l - u_k) \right] \quad (3)$$

For simplicity, consider the dynamics in (3) in vector form along with the communication TVDs can be written as:

$$\dot{u}(t) = Xu(t) + X_1 u(t - \tau(t)) \quad (4)$$

where, X and X_1 are constant positive $n \times n$ matrices; $\tau(t)$ is a time varying delay, $\tau(t) \in [0, h]$ is a bounded time varying delay and $h > 0$ (time delay). To derive the stability conditions for delay independent system, a Lyapunov function for (4) in terms of Riccati delay equation can be given as:

$$V(t, u_t) = u^T(t) G u(t) + \int_{t-\tau(t)}^{t} u^T(s) H u(s) ds \quad (5)$$

where, G and H are positive $n \times n$ matrices i.e. $G, H > 0$ and are positive definite and symmetric. In (5) it should be noted that V is dependent on t due to $\tau(t)$. However, in case of a constant delay i.e. $\tau = h$, then the Lyapunov function in (5) is time-independent i.e. $V(u_t)$. Moreover, in case of small varying communication delays it is assumed that τ is a derivative function with $\dot{\tau} \leq \kappa < 1$, where κ is any variable greater than zero. Taking the time derivative of (5) would give us:

$$\dot{V}(t, u_t) = 2u^T(t) G \dot{u}(t) + u^T(t) H u(t) - (1 - \dot{\tau}) u^T(t - \tau) G u(t - \tau) \quad (6)$$

Put (4) in (6) would yield us to:

$$\dot{V}(t, u_t) = 2u^T(t) G \left[Xu(t) + X_1 u(t - \tau(t)) \right] + u^T(t) H u(t) - (1 - \dot{\tau}) u^T(t - \tau) G u(t - \tau) \quad (7)$$

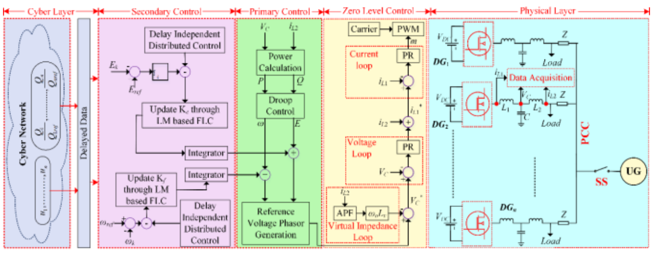

Fig. 1. Schematic of distributed control structure

Solving (7) according to a method presented in [9] would yield us to:

$$\dot{V}(t, u_t) \leq u^T(t) u^T(t - \tau) \begin{bmatrix} X^T G + GX + H & GX_1 \\ X_1^T G & -(1 - \kappa) H \end{bmatrix} \begin{bmatrix} u(t) \\ u(t - \tau) \end{bmatrix} \leq -\alpha |u(t)|^2 \quad (8)$$

for some $\alpha > 0$, if and only if (9)

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$$\begin{bmatrix} X^T G + GX + H & GX_1 \\ X_1^T G & -(1-\kappa)H \end{bmatrix} < 0$$

feasible for fast varying delays. Therefore, in this research work, for the fast varying time delays, the stability conditions are derived by using Razumikhin's method and applying a Lyapunov function. Let a Lyapunov function given below as:

$$V(u_t) = u^T(t) G u(t) \qquad (10)$$

According to Razumikhin's theorem [33, 34], when the condition

$$\sigma u^T(t) G u(t) - u^T(t-\tau(t)) G u(t-\tau(t)) \geq 0 \qquad (11)$$

holds for some constant $\sigma = 1 + \vartheta$, where, $\vartheta > 0$, it can be concluded that for any $\aleph > 0$, there exists $\beta > 0$ such that:

$$\begin{aligned} \dot{V}(u(t)) &= 2u^T(t) G\left[Xu(t) + X_1 u(t-\tau(t))\right] \\ &\leq 2u^T(t) G\left[Xu(t) + X_1 u(t-\tau(t))\right] + \\ &\aleph\left[\sigma u^T(t) G u(t) - u^T(t-\tau(t)) G u(t-\tau(t))\right] \\ &\leq -\beta |u(t)|^2 \end{aligned} \qquad 12$$

If

$$\begin{bmatrix} X^T G + GX + \aleph G & GX_1 \\ X_1^T G & -\aleph G \end{bmatrix} < 0 \qquad (13)$$

From (12) and (13) it can be observed that the matrix inequality neither depends on h nor on the delay derivative term as there is no constraint on delay derivative. Hence, the feasibility of (12) is sufficient for delay independent stability of an MG having fast TVDs. Moreover, a Lyapunov function based LMI for slow varying delays presented in (8) for $\kappa = 0$ is less restrictive as compared the Razumikhin condition (12) presented for fast varying delays. Moreover, if (12) is satisfied then automatically (8) is satisfied with the same values of G and $H = \aleph G$.

D. Sensitivity Analysis

Considering (4), the characteristic equation can be written as:

$$\det \Delta(\lambda) = 0 \qquad (14)$$

where, the left hand side of (14) is called the characteristic function. According to [1] and analogous to the case of finite dimensions, the roots of (14) are called the characteristic roots of (4) and are given as:

$$\Delta(\lambda) = \lambda I_n - X + X_1 e^{-\lambda\tau} \qquad (15)$$

As the spectrum of (15) is associated with communication delays, an approximation technique discussed in [36] is adopted to analyze (15) i.e., the eigenvalues of discretization matrix W can be given as:

$$W = \frac{\hat{\pounds} \otimes I_N}{X_1 \quad 0 \quad \mathrm{K}\,\mathrm{K} \quad 0 \quad X} \qquad (16)$$

where, $\otimes$ is the Kronecker product, I_N is the identity matrix of order *n*, the denominator presents the boundary conditions i.e. $X_1 = -\tau$ to $X = 0$, the matrix $\hat{\pounds}$ consists of first $n-1$ rows of the matrix £ and is described as:

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$$\pounds = -\frac{2D_n}{\tau} \qquad (17)$$

where, D_n is defined as the Chebyshev's differentiation matrix of the order $(n+1)\times(n+1)$. Initially, $(n+1)$ Chebyshev's nodes are define i.e., the interpolation points on the normalized interval $[-1,1]$ and are given as:

$$z_\gamma = \cos(\gamma\pi/n) \qquad (18)$$

where, $\gamma = 0,1.2,.........,n$. The entries of D_n are presented as :

$$D_{(k,l)} = \begin{cases} \dfrac{\mathrm{X}_k (-1)^{k+l}}{\mathrm{X}_j (z_k - z_l)} &, k = l \\ -\dfrac{z_k}{2(1-z_k^2)} &, k = l \neq 0,\ n \\ \dfrac{2n^2+1}{6} &, k = l = 0 \\ -\dfrac{2n^2+1}{6} &, k = l = n \end{cases} \qquad (19)$$

where, $z_0 = z_n = 2$ and $\mathrm{X}_1 = \mathrm{X}_2 = ... = \mathrm{X}_{n-1} = 1$. From the above notion, it can be concluded that the eigenvalues will appear on the left side of the plane that explains that a system will remain stable even for the large TVDs as presented in Fig. 2. Moreover, it is also noted that as the time delay swells, the effects are more prominent.

IV. Distributed voltage Regulation and Reactive Power Sharing Controller

A DAPI controller for voltage regulation and reactive power sharing can be given as:

$$E_k = E_{ref} - n_k Q_k + v_k \qquad (20a)$$

$$\frac{dv_k}{dt} = K_E\left[\sum_{l=1}^{n} b_{kl}\left[(Q_l/Q_{lref}) - (Q_k/Q_{kref})\right] - \Omega_k (E_k - E_{ref})\right] \qquad (20b)$$

where, E_k is the measured voltage of the k^{th}-DG (*k* = 1, 2,………, *n*); E_{ref} is the grid voltage; n_k is a (reactive power-voltage) $Q-E$ droop coefficient and is given as:

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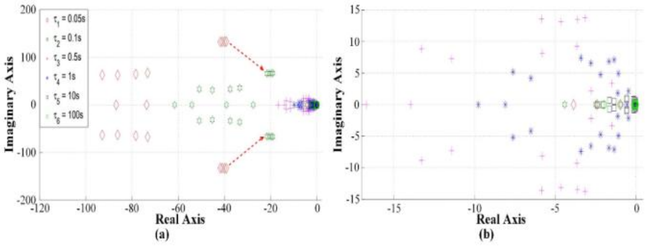

Fig. 2. Impact of communication TVDs on root loci, n = 5 (a) zoom-out view and (b) zoom-in view.

$n_k = \Delta E_k / Q_{k\max}$; of v_k is the SC variable; K_E and Ω_k are the designed SC positive gain; if a communication-link between k^{th}-DG and l^{th}-DG is present then $b_{kl} = 1$, otherwise, $b_{kl} = 0$. An adjacency matrix is presented as $B = \{b_{kl}\}$ and to avoid extra communication channel for simplicity it is considered that $B = A \Rightarrow \{b_{kl}\} = \{a_{kl}\}$.

As discussed in Section 2 and presented in Fig. 2, in a distributed control strategy, the exchange of information is performed a sparse communication network. Hence, in case of any communication time delay a DG will receive a delayed information that can affect the system stability. Therefore, to cope with this issue a DAPI controller in 20(b) can be rewritten as:

$$\frac{dv_k}{dt} = \sum_{l=1}^{n} b_{kl}\left[Q_l^{\oplus} - Q_k^{\oplus}\right] \qquad (21)$$

where, $Q_k^{\oplus} = Q_k / Q_{kref}$ and $Q_l^{\oplus} = Q_l / Q_{lref}$ are written for simplicity. Moreover, the constant and the voltage regulation terms are ignored, as no communication is involved in these terms. The dynamics in (21) along with the communication delays are written in vector form as:

$$\dot{v}(t) = Yv(t) + Y_1 v(t - \tau(t)) \qquad (22)$$

where, Y and Y_1 are constant positive $n \times n$ matrices; $\tau(t)$ is a time varying delay, $\tau(t) \in [0, h]$ is a bounded time varying delay. From (22) it can be observed that it is same as (4), therefore, a stability conditions can be derived by using a same methodology as discussed in Section 3.

V. Performance Validation

The performance of the proposed controller is validated through simulations, performed in MATLAB/SimPower software. A MG under consideration consists of four DGs (DG_1-DG_4), one public load (L_0), four local loads (L_1-L_4), and four transmission lines whose impedances are labelled as (Z) as presented in Fig. 3. The parameters values used in this study are tabulated in Table 1. The performance and effectiveness of the controller is examined in different case scenarios that are elaborated below.

TABLE I. PARAMETERS OF MG TEST SYSTEM

Parameter		Symbol	Value
Electrical Parameters			
Nominal Voltage		E	310 V
Frequency	Nominal	f	50 Hz
	Switching	f_{sw}	10×10^{-3} Hz
	Sampling	f_a	$1/1\times10^{-6}$ Hz
Line Impedance		Z_{12}	0.9 Ω + 4 mH
		Z_{23}	1.2 Ω + 5 mH
		Z_{34}	0.8 Ω + 3 mH
		Z_{14}	1.6 Ω + 6 mH
Load (P+Q)		$L_1 = L_2 = L_3 = L_4$	1 kW + 1 kVar
Primary Controller Parameters			
Droop coefficients		m_i (P-ω)	10^{-5} rad / (W s)
		n_i (Q-E)	10^{-3} V/Var
SC frequency gain		K_f	0.1
SC voltage gain		K_E	0.01
LCL Filter Parameters			
Inverter-side inductor		L_i	1.74×10^{-4} H
Grid-side inductor		L_g	1.2×10^{-3} H
LCL capacitance		C_f	3.31×10^{-5} F

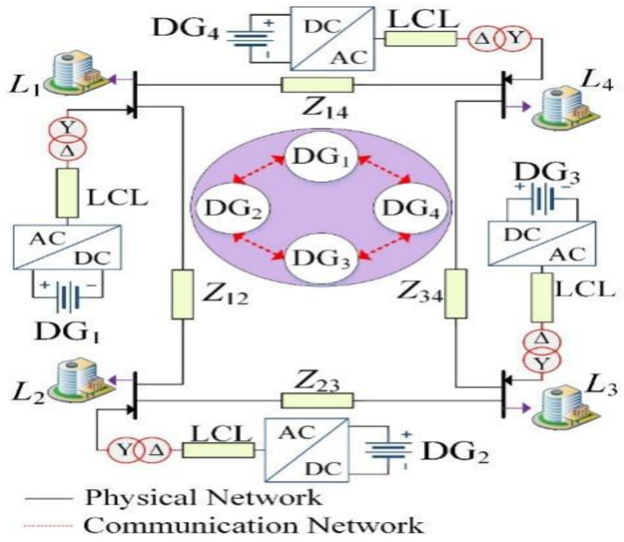

Fig. 3. Schematic of an MG under consideration.

A. Plug and Play Functionality

As the renewable energy generating units are intermittent in nature, therefore an MG must have the capability to perform PnP functionality. Therefore, the controller must have to perform effectively during PnP operation, achieve the consensus among the DGs, and ensure the system stability. Hence, in this scenario, it is considered that a DG_5 is plug-in to the bus 4 of an MG at t = 2 sec and plug-out at t = 4 sec as presented in Fig. 4.

Initially, the small communication delays i.e. τ = 0.05 sec are considered to show the effectiveness of proposed controller. The simulation results of proposed controller during PnP operation with small communication delays are presented in Fig. 5. It can be observed that at t = 2 sec, when a DG_5 is plug-in into the system some deviation in frequencies and voltages of the DGs is observed but the controller stabilizes these deviations very effectively and at about 0.4 sec they comes to their reference values. At the same time when DG_5 is plug-in, the controller achieves a new power

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consensus and share the load among all the DGs. Similarly, at t = 4 sec when a DG_5 is plug-out, same frequencies and voltages deviations are observed but the controller response very effectively and reach to their reference levels very rapidly. Fig. 5 shows that the controller perform very effectively for small communication time delays however to show the controller performance under PnP operation having large communication delays the τ is selected as 0.5 sec. The simulation results of this case having τ = 0.5 sec are presented in Fig. 6. From Fig. 6 it can be seen that even for the large delays the proposed controller regulate the voltages and frequencies of the DGs and maintain power consensus.

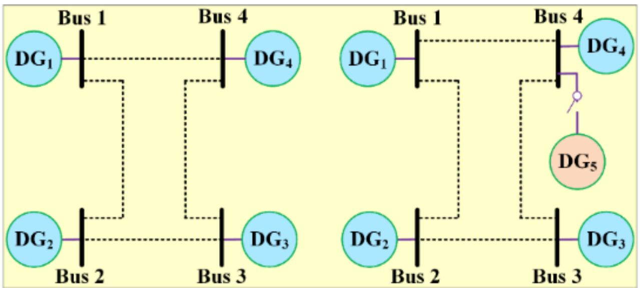


Fig. 4. MG topology during (a) normal operation and (b) PnP functionality.

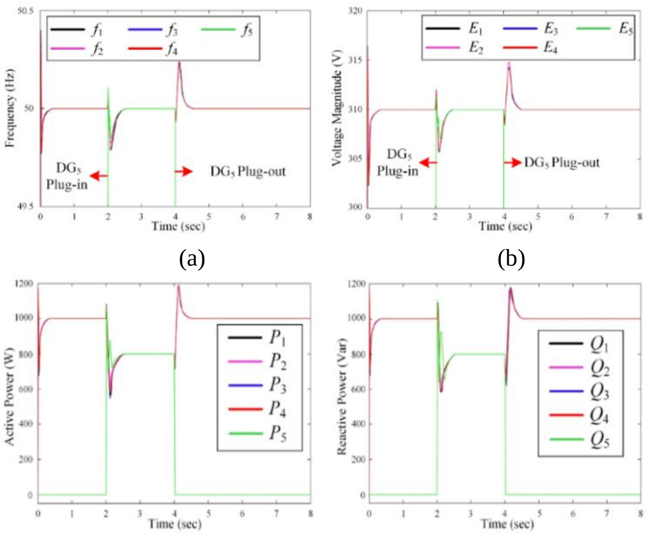


Fig. 5. Performance of the controller under PnP operation with small communication delays (τ = 0.05 sec) (a) *f*, (b) *E*, (c) *P*, and (d) *Q*.

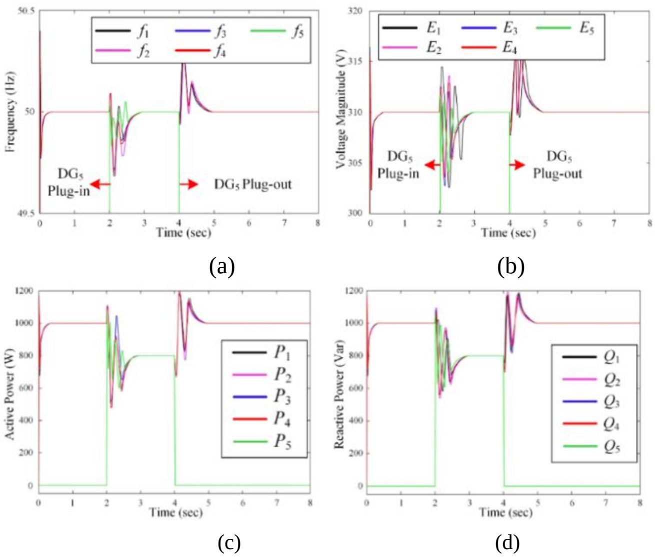


Fig. 6. Performance of the controller under PnP operation with large communication delays (τ = 0.5 sec) (a) *f*, (b) *E*, (c) *P*, and (d) *Q*.

B. Robustness to Load variation

In this scenario, the performance of the controller is validated for varying load condition with slow and fast varying communication delays. Initially, all the load i.e. $L_1 = L_2 = L_3 = L_4$ = 1 kW + 1 kVar are set for $0 \leq t \leq 2$ sec. Then all the loads are varied i.e. $L_1 = L_2$ = 0.5 kW + 0.5 kVar (becomes half) and $L_3 = L_4$ = 2 kW + 2 kVar (becomes double) during the time $2 \leq t \leq 4$ sec. At t = 4 sec all the load varies again and comes to its initial state i.e. $L_1 = L_2 = L_3 = L_4$ = 1 kW + 1 kVar.

The Fig. 7 (small delays τ = 0.05 sec) it can be seen that as the load varies a small deviation is observed in frequency i.e. around 0.2 Hz and voltage i.e. around 3.5 V in output waveforms. These deviations are restore by the controller very effectively and come to its reference level within 0.55 sec. At the same time as the load varies a new power consensus is attained by the controller and share the load among all the DGs. Similarly, in case of the large communication delays i.e. τ = 0.5 sec, an MG is subjected to same pattern of load variation. In Fig. 8, same frequencies and voltages deviations are observed at an instant when the load varies. But the controller restore these deviation and approximately within 1.1 sec they comes to its steady-state with a maximum deviation of 0.4 Hz in frequency and 8.5 V in voltage.

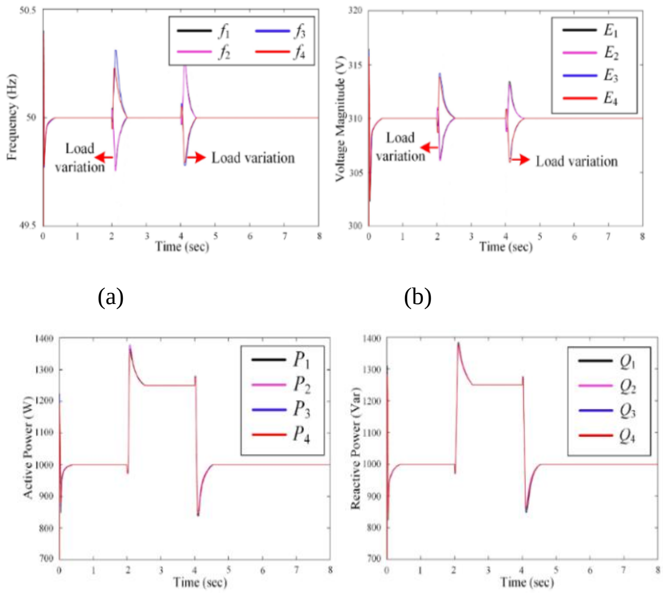
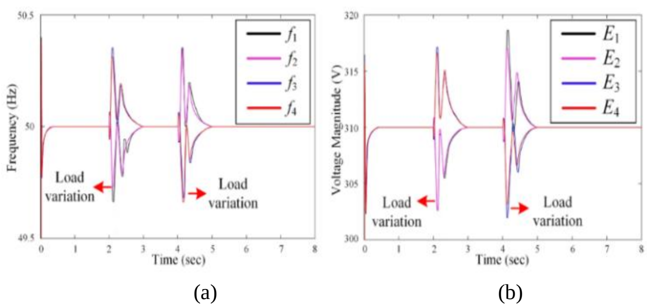


Fig. 7. Performance of the controller under load variation with small communication delays (τ = 0.05 sec) (a) *f*, (b) *E*, (c) *P*, and (d) *Q*.



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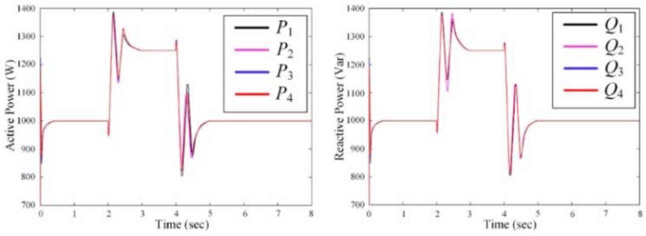

(c) (d)

Fig. 8. Performance of the controller under load variation with large communication delays (τ = 0.5 sec) (a) *f*, (b) *E*, (c) *P*, and (d) *Q*.

VI. Conclusion

A delay independent DAPI control scheme incorporated in an MG system for frequency and voltage regulation and power sharing is proposed in this manuscript. The proposed control scheme minimizes the error and maintains system frequency and voltage at reference value and ensure appropriate power sharing although small and large varying communication delays were subjected. The simulation results shows that the voltages and frequencies of the DGs are restored to their references very effectively while ensuring appropriate power sharing under PnP operation and load variation condition. In a future, it is aim to investigate the distributed secondary control scheme considering stochastic communication delays and network attack.

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