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Decentralised-Distributed Secondary Frequency Restoration and Power Sharing Control for Microgrid Clusters

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***Abstract*— A scalable decentralised-distributed secondary control architecture for frequency restoration and power sharing control in MicroGrid (MG) clusters, is proposed in this paper. The proposed scheme allows to reduce the communication cost of classical distributed control schemes, thus possibly reducing privacy and security concerns, while guaranteeing scalability properties, by adopting a leaky integral controller. Based on the droop control mechanism, the model for Alternating Current (AC) MG clusters is considered. A leader-follower-based decentralised-distributed secondary control is then designed for frequency restoration and active power sharing among and within clusters, respectively. The parameters selection for the proposed controller is also analysed and simulations show the effectiveness of the proposed decentralised-distributed control method.**

I. INTRODUCTION

Due to a continuously increasing diffusion of Renewable Energy Sources (RESs), the MG paradigm is expected to expand its scale to meet the corresponding requirements. MG clusters that connect multiple MGs together are emerging to improve energy efficiency and enhance system resilience [1]. However, how to design efficient secondary control methods for frequency restoration and active power sharing in MG clusters is still an under-explored problem.

To realise the secondary control for MGs, three main control approaches have been proposed in the literature [2]: centralised, decentralised and distributed. Centralised control schemes take the measurements from the MG and send the corresponding control signal to each Distributed Generator (DG) by using a MG Central Controller (MGCC) [3]. However, an MGCC may be sensitive to faults since the entire system will be compromised in the case the MGCC fails to operate appropriately. In addition, as DGs are gradually becoming more and more spatially distributed, the realization of an MGCC may result impractical or unfeasible due to communication and computation constraints. Decentralised control algorithms have then been proposed to overcome these shortcomings, by equipping each DG unit with a local controller. In this scenario, each DG is controlled based on local information only [4], but in this way it may be difficult to achieve global optimisation and management objectives. To address the above-mentioned drawbacks, distributed control architectures have been proposed, where each MG cluster is allowed to communicate with its neighbours, thus possibly enhancing flexibility, stability and resilience goals [5], [6]. For example, to address unstructured uncertainties and communication delays, an H_∞ secondary control method integrated with a virtual synchronous machine technology is proposed in [7] for low-voltage MG clusters. Although distributed controllers present the advantages deriving from overall having available the global information from each DG, they may suffer from heavy communication cost in MG clusters. In addition, some agents may be unwilling to share their information with neighbours due to cyber-security and privacy concerns.

Furthermore, the structure of the overall system may change over time, due to for example revamping, maintenance, faults or addition of new DGs or of new clusters [8], [9]. To adapt to the possibly time-varying interconnections of MG clusters, a question naturally arises: ***Is it possible to design a general control framework able to realise frequency restoration and power sharing control in scalable time-varying scenarios including both decentralised and distributed MG clusters?*** To solve this problem, this paper proposes a novel decentralised-distributed control method able to integrate the benefits of both decentralised and distributed control, that is achieving global objectives while reducing the required communication. In the considered MG clusters, each cluster identifies one leader DG responsible for receiving frequency information from the bus, without requiring information exchange between leader DGs among different clusters, thus ensuring the decentralisation. Within each MG cluster, the leader DG communicates with other follower DGs in a distributed manner. Compared with the distributed framework where indirected graphs are used to describe the connection [10], the proposed framework uses directed graphs to formulate the cyber connection with less communication burden. Then, a novel leaky integral decentralised-distributed secondary controller is designed to restore frequency and realise power sharing control, obtaining tolerant steady-state errors but requiring less communication information than classical distributed schemes, specifically not requiring communication among leaders of different clusters. A set of simulation results is analysed to validate the proposed method. Finally, the plug-and-play ability [8], [9], fundamental to guarantee the scalability of the system, is verified in simulation.

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II. Problem Formulation And Objectives

In this section, Alternating Current (AC) MG clusters are introduced with the droop control scheme for each inverter-based DG unit. Besides, the control objectives are discussed in detail.

Due to the continuously increasing importance of renewable energy resources in the grid, it is crucial for control methods to be effective in 100% inverter-based MGs [11]. Therefore, this paper considers general clusters where 100% inverter-based RESs and local loads are present. The considered MG system (see Fig. 1) is composed of n MG clusters [1], where N_k DGs are connected in parallel to the AC bus in each cluster $k = 1, \dots, n$. The cyber connection between DGs is assumed to be reliable, secure and synchronized. It should be mentioned that, in general, MG clusters refer to sets of MGs [1]. However, since the purpose of this paper is to control DGs to realise frequency restoration and power sharing, in this paper we do not model each MG inside each cluster, but we directly consider the resulting network of DGs in each cluster. The entire MG system can be represented as a weighted graph $\mathscr{G} = (\nu, \xi)$. Each DG is a node of the graph, where the set of the nodes can be denoted as $\nu = \{(1,1), (1,2), \cdots, (1, N_1), (2,1), \cdots, (n, N_n)\}$. ξ is the set of the edges, which represent the impedance between buses. Let define the set of neighbor nodes of the ith node in the kth MG cluster as $\mathscr{N}_{k,i} \triangleq \{j \in \nu | (i,j) \in \xi\}$.

By defining the measured active power $P^m_{k,i}$ for each ith DG ($i = 1, \dots, N_k$) within each kth cluster ($k = 1, \dots, n$), the following frequency dynamic equation is given based on the droop control function [12]: $w_{k,i} - w^{ref} = \mathcal{K}_{k,i}(P^m_{k,i} - P^{ref}_{k,i})$, where w^{ref} is the desired frequency, $P^{ref}_{k,i}$ is desired active power outputs and $\mathcal{K}_{k,i}$ is the droop coefficient. By using a first-order low-pass filter while ignoring fast dynamics, it can be obtained that $T_{k,i}\dot{P}^m_{k,i} = -P^m_{k,i} + P_{k,i}$, where $T_{k,i}$ is the time constant of the filter, $P_{k,i}$ is the active power output of the ith DG of the kth cluster. Combining the above two equations, the following DG model can be derived as

$$T_{k,i}\dot{w}_{k,i} + w_{k,i} - w^{ref} + \mathcal{K}_{k,i}(P_{k,i} - P^d_{k,i}) = 0, \qquad (1)$$

According to the power balance relationship in this MG system, the actual injected (or absorbed) power of the ith DG in the kth MG cluster is given by $\hat{P}_{k,i} = \sum_{j \in \mathscr{N}_{k,i}} V^2 \left|B_{(k,i,j)}\right| \sin(\delta_{k,i} - \delta_{k,j})$, where $\delta_{k,i}$ is the phase angle and $B_{k,i,j}$ is the susceptance between the ith bus and the jth bus in the kth cluster. It should be noted that, in general, voltage control should be first achieved for NMGs before restoring the frequency. There are several methods proposed for the voltage control in the literature [5], [12], [13]. Hence, to focus on frequency restoration, this paper assumes that the voltage level is the same at each cluster, i.e., V represents the voltage value of every cluster. On the other hand, the local load of the ith DG in the kth MG cluster is defined as $L_{k,i}$, then the total output power of the ith DG in the kth MG cluster can be expressed as

$$P_{k,i} = L_{k,i} + \hat{P}_{k,i}. \qquad (2)$$

As illustrated in Fig. 1, each cluster designates one DG as the leader DG (represented in pink in Fig. 1) which can receive the frequency signal from the AC bus and maintain the decentralisation between clusters. The leader DG will communicate its input signals to the follower DGs (shown in blue in Fig. 1).

Based on the DG model (1) and the output power (2), the control objectives of MG clusters can be summarized as: 1) To restore the frequency to the desired value w^{ref} for each ith DG in the kth cluster, i.e.: $\lim_{t\to+\infty} w_{k,i}(t) = w^{ref}, \forall i \in \{1, \dots, N_k\}, k \in \{1, \dots, n\}$; 2) To ensure the actual power sharing within each MG cluster. Within the kth ($k = 1, \cdots, n$) cluster, the actual output power ratio of ith/jth DG should follow: $\lim_{t\to+\infty} \frac{P_{k,i}(t)}{P_{k,j}(t)} = \frac{\mathcal{K}_{k,j}}{\mathcal{K}_{k,i}}, \forall i,j = 1, \cdots, N_k$ and the active power between the kth cluster and the mth cluster should also be guaranteed to be in a certain ratio, i.e.: $\lim_{t\to+\infty} \frac{P_k(t)}{P_m(t)} = \frac{\beta_k}{\beta_m}, \forall k, m = 1, \cdots, n$, where $P_k(t) = \sum_{i=1}^{N_k} P_{k,i}(t)$ and $P_m(t) = \sum_{i=1}^{N_k} P_{m,i}(t)$ are the power outputs of the kth and mth MG cluster, respectively. β_k and β_m are the optimal power allocation ratios, and will be discussed in Part B, Section III.

III. Decentralised-Distributed Secondary Controller

To restore the frequency, an auxiliary control variable $u_{k,i}$ is added to the system (1) of each DG in the MG cluster and the model can be rewritten as follows:

$$T_{k,i}\dot{w}_{k,i} + w_{k,i} - w^d + \mathcal{K}_{k,i}(P_{k,i} - P^d_{k,i}) + u_{k,i} = 0. \qquad (3)$$

To easily analyse the control errors, we define for each ith DG in the kth MG cluster, the frequency error as e^w and the secondary control auxiliary variable error as e^u represented by the following equations:$e^w_{k,i} = w_{k,i} - w^{ref}$, $e^u_{k,i} = \sum_{j \in \mathscr{N}_{k,i}} (u_{k,j} - u_{k,i})$. Inspired by the leaky integrator [14], a novel distributed leaky integral secondary controller is designed as

$$\sigma_{k,i} u_{k,i} = \int \Big(\theta_{k,i}(e^w_{k,i} - \eta_{k,i} u_{k,i}) + (1 - \theta_{k,i}) e^u_{k,i}\Big) dt, \qquad (4)$$

where $\sigma_{k,i} \in \mathbb{R}^+$, $\eta_{k,i} \in \mathbb{R}^+$ are the tuning controller parameters. The value of $\theta_{k,i}$ is either 1 when DG is the leader in the MG cluster or 0 otherwise. Fig. 2 depicts the control framework of the proposed primary-secondary layers, where it is observed that, in the proposed decentralised-distributed controller, if DG is a leader, the controller (4) will be a completely leaky integral controller, and the leader can receive the frequency information from the bus. If the DG is a follower, it only receives the signal $u_{k,j}$ from the neighbors. Under directed graph, the controller can be transformed

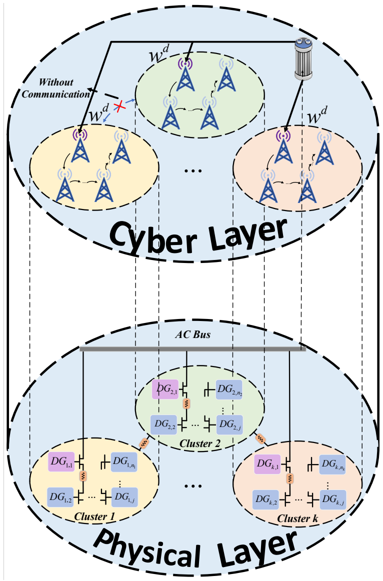

Fig. 1. The physical and cyber framework for MG clusters

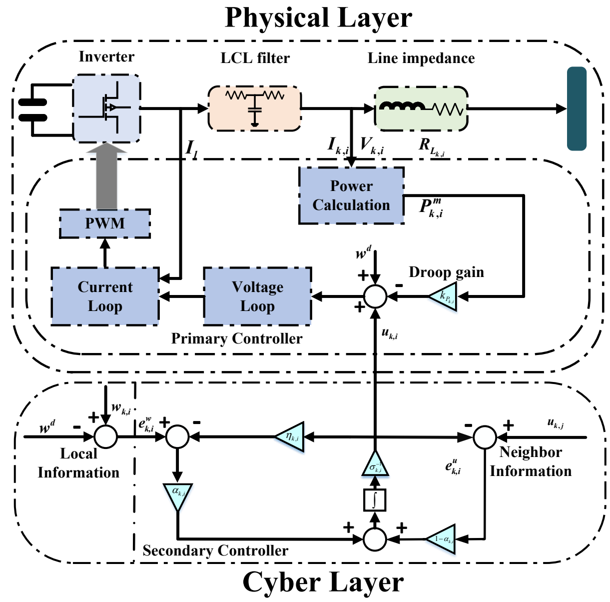

Fig. 2. The considered control framework

into the following compact form: $\sigma u = \int \Big(\theta(e^w - \eta u) - (I-\theta)\mathscr{L}u\Big)dt$, where $\mathscr{L}$ is an upper or lower triangular Laplacian matrix.

Notice that the selection of the optimal power allocation ratios β_k and β_m will affect the power sharing and the frequency restoration [15], [16]. Hence, in what follows, the parameter selection will be analysed.

It is known that, except for some extreme situations like encountering the power disruption, controllers can generally make MGs convergent to steady states. Hence, we assume that for the system (3) and the controller (4), there exists a steady-state solution $(e^{ws}_{k,i}, P^s_{k,i}, u^s_{k,i})$ satisfying the following equations:

$$e^{ws}_{k,i} + \mathcal{K}_{k,i}P^s_{k,i} + u^s_{k,i} = 0, \tag{5}$$

$$\theta(e^{ws} - \eta u^s) - (1-\theta)\mathscr{L}u^s = 0, \tag{6}$$

where $e^{ws} = w_{ss} - w^{ref}$ is the steady-state frequency error, $P^s_{k,i}$ and $u^s_{k,i}$ represents the steady-state values of $P_{k,i}$ and $u_{k,i}$ of the ith DG in the kth MG cluster.

According to (5) and (6), the parameter analysis among MG clusters (denoted as inter cluster) and within each MG cluster (denoted as intra cluster) are discussed, respectively:

Inter Cluster: In this case, the leader DGs in each MG cluster is analysed, where $\theta = 1$ holds and Eq. (6) can be rewritten as:

$$e^{ws} - \eta u^s = 0, \tag{7}$$

Combining Eq. (5) and Eq. (7), the following equation can be derived

$$(1+\eta^{-1})e^{ws} + \mathcal{K}P^s = 0, \tag{8}$$

and Eq. (8) indicates that the relationship between leader DGs follows:

$$\frac{P^s_{k,lea}}{P^s_{M,lea}} = \frac{\mathcal{K}_{M,lea}(1+\eta^{-1}_{k,lea})}{\mathcal{K}_{k,lea}(1+\eta^{-1}_{M,lea})}, \tag{9}$$

where subscript 'lea' denotes the parameters of each leader DG. To realise the frequency restoration while satisfying the power allocation, it is necessary to select the appropriate control parameter $\eta > 0$. By taking the sum of the Eq. (8) from $k = 1, ..., N_k$, we can derive that, for any $\epsilon > 0$, if the following inequality is satisfied

$$\sum_{k=1}^{n} \eta^{-1}_{k,lea} \geq \frac{\sum_{k=1}^{n} \mathcal{K}_{k,lea}P^s_{k,lea}}{\epsilon} - \sum_{k=1}^{n} N_k, \tag{10}$$

then $||e^{ws}|| < \epsilon$ holds and the frequency is restored. The optimal power allocation ratios β_k and β_m are expressed as $\frac{\beta_k}{\beta_M} \triangleq \frac{\mathcal{K}_{M,lea}(1+\eta^{1}_{k,lea})}{\mathcal{K}_{k,lea}(1+\eta^{1}_{M,lea})}$.

Intra Cluster: In this case, we analyse the leader DG and follower DG in the same MG cluster and by setting $\theta = 0$, Eq. (7) can be rewritten as $-\mathscr{L}u^* = 0$ and this equation shows that $u_{k,i}$ of each DG within the same MG cluster reaches consensus, i.e., $u^s_{k,1} = u^s_{k,2} =, \cdots, = u^s_{k,N_k}$. From the analysis of Eq. (7) in the inter cluster, we can obtain the input of the leader is $\eta^{-1}e^{w*}_{k,lea}$. Therefore, the consensus control input of each follower DG is $u^s_{k,1} = u^s_{k,2} =, \cdots, = u^s_{k,N_k} = \eta^{-1}e^{ws}_{k,lea}$, and the active power distribution in the same cluster can be expressed as

$$\frac{P^s_{k,i}}{P^s_{k,j}} = \frac{\mathcal{K}_{k,j}}{\mathcal{K}_{k,i}}. \tag{11}$$

Based on the above-mentioned analysis, we can conclude that through the proposed controller and selecting appropriate parameters σ and η, Eqs. (9) (10) (11) can be realised simultaneously.

Remark 1: If the leader DG becomes disconnected from the rest of the cluster due to any reason, the first follower can be allocated as a new leader and the disconnected leader will form a separate cluster in a decentralized manner. In this

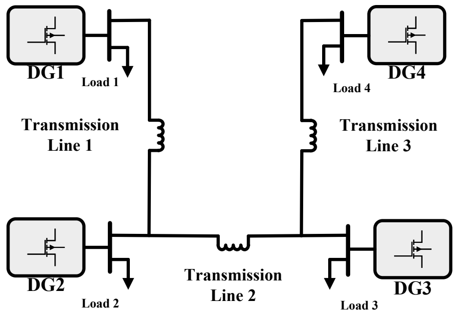

Fig. 3. Physical connection of the test system.

TABLE I
PARAMETERS OF DGS AND PRIMARY CONTROLLER

	Parameter	DG1	DG2	DG3	DG4
Desired Frequency	w^{ref}	50Hz			
Filter Constant	$T_{k,i}$	0.079			
Load	L_i	100 Ω per phase			
Line Resistance	R_i	0.6 Ω			
Line Inductance	L_i	0.03393 H			

case, the allocation of the active power sharing may change, but the proposed method will still be valid.

IV. SIMULATIONS

In order to verify the effectiveness of the proposed decentralised-distributed secondary controller, multiple MG clusters scenarios are simulated in MATLAB/Simulink and tested by changing the number of DGs, communication topology, and controller parameters. In the whole simulation, the first DG of each MG cluster is chosen as the leader to receive bus frequency information. The physical connection of the test system is illustrated in Fig. 3 and the parameters of DGs and primary controller are summarized in Table I [12]. Each local load is connected to each DG bus, and the droop gain of these 4 DGs is set to $\mathcal{K}_1 : \mathcal{K}_2 : \mathcal{K}_3 : \mathcal{K}_4 = 6 : 3 : 2 : 1$. The reference frequency value is $w^{ref} = 50.00$Hz.

A. The proposed method in a decentralised-distributed hybrid scenario

In this section, the performance of our proposed method in a partially decentralised, partially distributed communication topology scenario is investigated. The communication graph is shown in Fig. 4, where $DG1$, $DG2$, $DG3$ are clustered as $DG_{1,1}$, $DG_{1,2}$, $DG_{1,3}$ in the 1^{st} MG cluster, and $DG4$ is redefined as $DG_{2,1}$ in the 2^{nd} MG cluster. The parameters of the secondary controller are shown in Table II. It can be seen from Fig. 5 that before the secondary control is started, the system frequency of the MG cluster is at 49.42Hz due to droop control. And after activating our proposed secondary control method, the system frequency can quickly restore to the reference value w^{ref} and the output active power of the system is sharing ratio according to Eqs. (9) and (11).

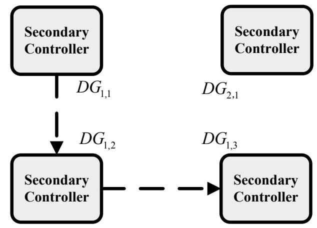

Fig. 4. Communication graph in case A.

TABLE II
PARAMETERS OF SECONDARY CONTROLLER IN CASE A

	Parameters	DG1	DG2	DG3	DG4
Secondary Controller	σ_{k_i}	1e-4			
	θ_{k_i}	1	0	0	1
	η_{k_i}	5e-3	/	/	1e-2

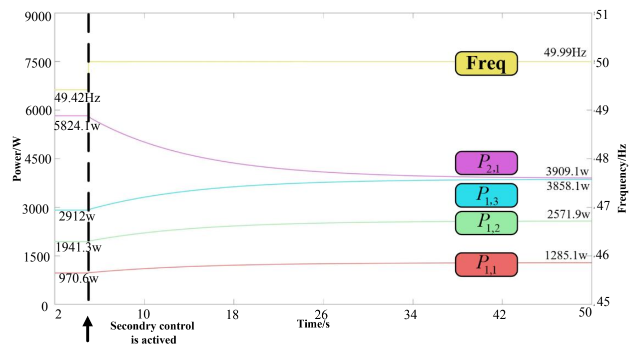

Fig. 5. Frequency and active power output in case A.

B. The proposed method in a completely distributed scenario

It is important to note that one of the advantages of the proposed method is that it can adapt to different interconnection frameworks. To verify this property, in this section the proposed controller is tested in a totally distributed framework. The communication graph is shown in Fig. 6, where $DG1$, $DG2$ are grouped as $DG_{1,1}$, $DG_{1,2}$ in the 1^{st} MG cluster, and $DG3$, $DG4$ are $DG_{2,2}$, $DG_{2,1}$ in the 2^{nd} MG cluster. The parameters of the secondary controller are shown in Table III. The frequency and active power output are shown in Fig. 7, where we can see that the frequency remains at 49.42Hz until the second layer control is activated. After the activation of the proposed secondary control, the frequency is restored to 50.00Hz. The phenomenon of $P_{1,1} : P_{1,2} : P_{2,1} : P_{2,2} \approx 2 : 4 : 3 : 6$ is in line with the Eqs. (9) and (11), which further verifies that our proposed controller is suitable for the active power distribution.

C. The proposed method and the plug-and-play feature

In this case, the plug-and-play feature of the proposed secondary controller is also tested by disconnecting and reconnecting $DG_{2,1}$ to the 2^{nd} MG cluster, assuming that

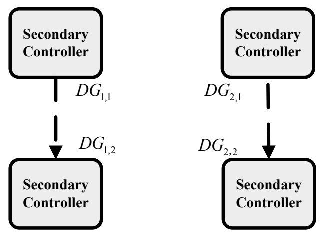

Fig. 6. Communication graph in case B.

TABLE III
PARAMETERS OF SECONDARY CONTROLLER IN CASE B

	Parameter	DG1	DG2	DG3	DG4
Secondary Controller	σ_{k_i}	1e-4			
	θ_{k_i}	1	0	0	1
	η_{k_i}	5e-3	/	/	1e-2

the communication graph remained connected when $DG_{2,1}$ disconnected. The physical connection, parameters, and communication diagram are the same as in case A. As shown in Fig. 8, when $DG_{2,1}$ is disconnected from the 2^{nd} cluster, the proposed secondary controller can keep the DGs of all clusters at 50.00Hz, and the power outputs are redistributed based on the rules of allocating by droop gain within the cluster. When $DG_{2,1}$ is reconnected, the frequency and power output can be restored to the previous values. These preliminary results show that the proposed control method has plug-and-play capabilities in the comsidered scenario.

D. Scalability of the proposed method on the number of MG clusters

This section considers a slightly larger MG cluster systems than the previous sections with six DGs to form three clusters. The physical and cyber connection frameworks of the MG system are shown in Figs. 9 and 10. The parameters of the system are given as: droop gains of the 6 DGs $\mathcal{K}_1 : \mathcal{K}_2 : \mathcal{K}_3 : \mathcal{K}_4 : \mathcal{K}_5 : \mathcal{K}_6 = 6:3:2:1:9:3$, leader-follower gains $\theta_{1,1} = \theta_{2,1} = \theta_{3,1} = 1$ and $\theta_{1,2} = \theta_{3,2} = \theta_{3,3} = 0$,

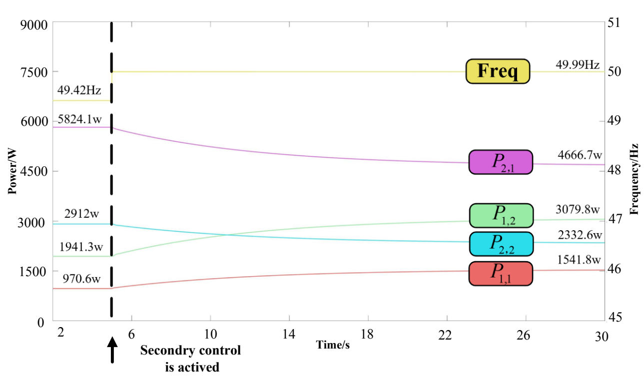

Fig. 7. Frequency and active power output in case B.

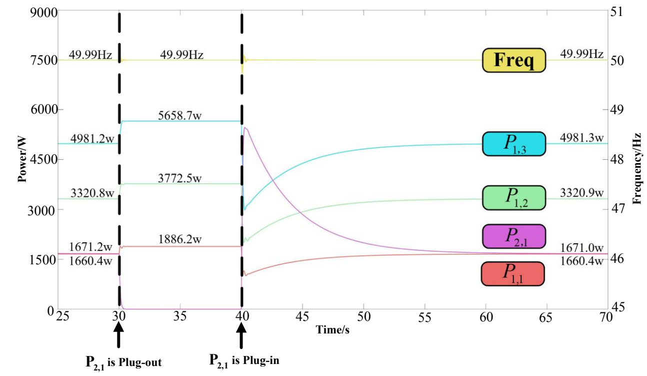

Fig. 8. Frequency and active power output in case C.

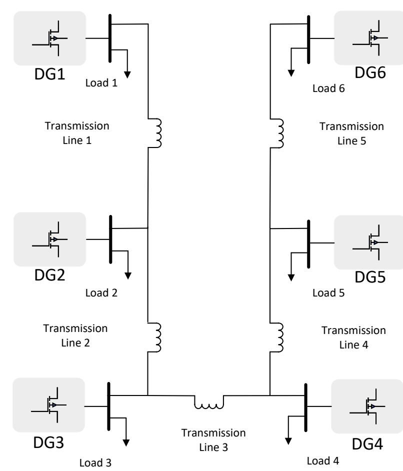

Fig. 9. The physical connection of 6 DGs.

controller parameters $\eta_1 = 0.005, \eta_2 = \eta_3 = 0.01$. Based on these parameters, the proposed secondary controller is performed and the corresponding results are shown in Figs. 11 and 12, where it can be observed that there exists a tolerable error in the frequency restoration. This phenomenon is in line with the controller analysis in Section III and we can still verify that the frequency restoration and the active power allocation are achieved simultaneously by using the proposed method.

Based on the above-mentioned results, it can be concluded that the proposed method is able to realise frequency restoration and power sharing control under several different and possibly time-varying interconnection frameworks without requiring communication between leaders among MG clusters. Specifically, this method also works for scenarios where there is only a single DG unit present in the cluster, showing its practical significance as DGs managed by each MG cluster may change due to varying demand in practical applications. Although they cannot show the same unbiased frequency restoration as the distributed control, the proposed method can realise the two control objectives with less communications and by tuning the control parameter η by Eq. (10), the steady-state error e^{ws} can be limited to the 10^{-3} level, which is close to the distributed control effect.

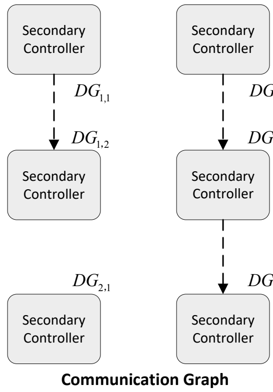

Fig. 10. The cyber connection of 6 DGs

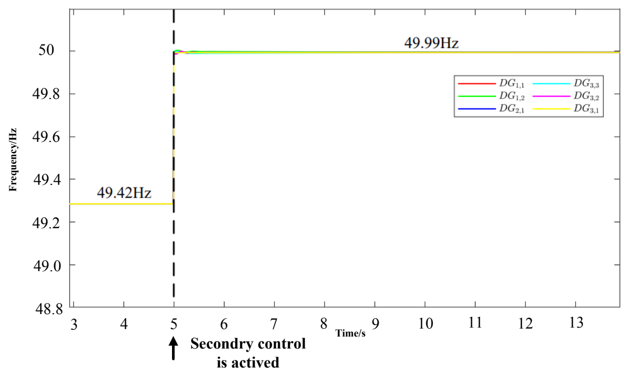

Fig. 11. Frequency trends for six DGs.

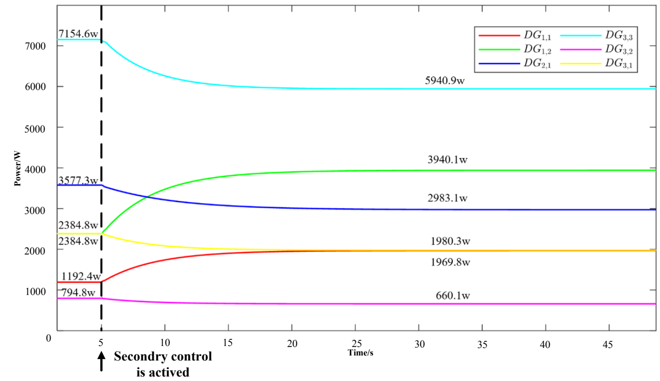

Fig. 12. Active power output for six DGs.

V. Conclusion

In this paper, preliminary results for a decentralised-distributed secondary control methodology based on the leaky integrator are presented for frequency restoration and power sharing of islanded AC MG clusters. The proposed method reduces the communication required in MG clusters compared to classical distributed approaches, with further potential advantages in terms of privacy and security. Simulations show that frequency restoration and power sharing can be achieved simultaneously by choosing appropriate control parameters and the proposed method is suitable for various communication frameworks, including plug-and-play scenarios. Since the leaders here are linked using a decentralised framework, the privacy of agents who are unwilling to share information can be preserved. However, they may vulnerable to cyber attacks due to the decentralisation. As a future work, we will test the proposed methodology on more complex models and benchmarks and we will formally investigate some of the properties of the proposed methodology, focusing on the resilience of the proposed method when encountering cyber-attacks in a large MG network.

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