This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2020.2985995, IEEE Transactions on Power Systems

Privacy-Preserving Distributed Control Strategy for Optimal Economic Operation in Islanded Reconfigurable Microgrids

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***Abstract*—In this paper, a privacy-preserving distributed control strategy is proposed for realizing the optimal economic operation of islanded reconfigurable microgrids (MGs). Using the proposed distributed control strategy, participating DERs would only exchange the frequency data with their neighbors while the generation data are held privately by each participant. The proposed distributed control strategy reduces the communication burdens among DERs and exploits the operational flexibility of reconfigurable MGs. It also demonstrates the versatility for considering a variety of operational objectives without requiring any additional communication and control infrastructures. Using the proposed control strategy, the optimality and the stability of an MG system's equilibrium point are demonstrated by the Lyapunov theory. The effectiveness of the proposed control strategy is validated in a 12-bus MG system for various operating conditions, including load variations, DER disconnection and reconnection operations, and MG reconfiguration operations.**

***Index Terms*— Reconfigurable microgrids, distributed control strategy, privacy-preserving, economic operation.**

NOMENCLATURE

A. Index and Sets:

i, j	Index of participating DERs
$(\cdot)^{rated}$	Rated value
$(\cdot)^{*}$	Equilibrium point
$(\cdot)^{T}$	Transpose of the matrix
$c_i(\cdot)$	Cost function of DER i
$diag(\cdot)$	Diagonal matrix whose diagonal elements are the values of the vector

B. Parameters:

a_i, b_i, c_i	Cost coefficients of DER i
N	Number of participating DERs
$\mathbf{A}$	Adjacency matrix of the communication network
$\mathbf{D}$	Degree matrix of the communication network
$\mathbf{L}$	Laplacian matrix of the communication network
m_i	Droop coefficient of DER i
α, β, γ_i	Positive control parameters

C. Variables:

P_i	Active power output of DER i
$P_{i,\max}, P_{i,\min}$	Maximum and minimum capacity limits of DER i
λ_i	Incremental cost of DER i
λ	Multiplier corresponding to system power balance constraint
$\bar{\mu}_i, \underline{\mu}_i$	Multipliers corresponding to the capacity constraints of DER i
$u_{\omega i}$	Designed control input by adjusting the frequency set point of DER i
e_i	State error of DER i
ω_i	Operating frequency of DER i
$\boldsymbol{\omega}$	Vector of DER frequencies
f_i	Local objective function of DER i

Other notations are defined in the text.

I. INTRODUCTION

THE increasing number of distributed energy resources (DERs) introduces randomness as well as strong controllability and observability concerns to modern power systems [1]. Microgrid (MG) provides a promising solution to accommodating and coordinating various DERs by forming a flexible and efficient electrical network [2]. MG is defined as a small-scale self-controllable power system connected to or islanded from distribution networks, which clusters and manages participating DERs within defined electrical boundaries [3]. For islanded MGs, the task of economic operation is defined as to economically coordinating participating DERs while satisfying power balance constraints.

Conventionally, the economic operation task is handled in a centralized control system in which a master controller (MC) is deployed to collect data from participating DERs and calculate operational set points for participants. With the increasing penetration of various DERs, Sun et al. have proposed a novel and efficient way to project future DER adoption accelerated by rate policies [4]. The paper is the first work to establish a theoretical framework for the equilibrium and stability of DER adoption level. Considering a multitude of participating DERs, the deployed MC requires extremely fast and reliable communication and computation capabilities for realizing real-time data collections and processing. Any failures in communication and control infrastructures would affect the overall MG performance in terms of efficiency and reliability. Moreover, centralized control system would lead to MG system fragility concerning single-point-failures [5].

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To overcome the drawbacks of centralized approaches, additional distributed monitoring and control approaches have been investigated recently, which provide a more robust and cost-effective regulation over MGs [6]. In a distributed control system, data collection and processing are handled by several affordable local controllers (LCs) instead of an expensive MC, which speed up the system response to variable DERs and loads cost-effectively [7]. Based on the equal incremental cost criterion (EICC), the incremental costs of participating DERs are considered as consensus variables which are regulated to be identical for minimizing the system operation cost [8]-[14]. In [8]-[10], the total demand is assumed to be known for each unit. In [11], a leader unit is considered which would collect the system power imbalance data and make adjustments corresponding to the calculated system incremental cost. The selection of leader and communication network topologies would affect the convergence rate of the adopted consensus-based algorithm. However, these methods are not fully distributed due to the strong assumption about the MG system's power imbalance [12]. In [13], an innovation term is added to the consensus term to consider the system power balance while the optimal solution may not be guaranteed due to the missing system power imbalance data. Then, a graph discovery algorithm is proposed while participating units and loads might encounter increased infrastructure costs and communication burdens, and slower system response [14]. Thus, the key challenge for such consensus-based approaches is to satisfy the system power balance constraint, which has not been well addressed in previous works since the optimal incremental costs of participating DERs are difficult to be predetermined.

In addition, some intelligent MGs could possess varying structures with dynamic boundaries, which are referred to as reconfigurable MGs in this paper [15]. By utilizing smart switches, reconfigurable MGs with an adjustable electrical network topology can be partitioned into several independent sub-MGs, such as the IIT campus MG with seven loops. Accordingly, the corresponding communication burdens should be further reduced to accommodate frequent reconfiguration operations. Also, in most existing distributed control strategies, sensitive information (e.g., generation data) exchanges throughout the communication network (e.g., active power outputs or incremental costs) imply that a participant's privacy might be compromised [16]. Potential privacy threats and associated cybersecurity issues would lower the willingness of participants to share their data and restrict the sustainable development of advanced communication and control applications [17]. For preserving the privacy of participating DERs, each participant's generation data should be privately-held locally and not be shared with other participants.

Therefore, we propose a privacy-preserving distributed control strategy for the optimal economic operation in islanded reconfigurable MGs with the following advantages:

1) The proposed distributed control strategy is privacy-preserving, in which only frequency data are shared among neighboring DERs while each participating DER's private information (i.e., generation data) is confined to the respective DER;

2) The proposed distributed control strategy provides the real-time optimal economic operation in islanded MGs for realizing the benefits of variable DERs effectively. In addition, the optimality and the asymptotical stability of the system equilibrium point are demonstrated using the Lyapunov theory. At the equilibrium point, participating DERs reach consensus on incremental costs and their frequencies will be synchronized at the rated value;

3) The proposed distributed control strategy retains the cost-effective operational merits of reconfigurable MGs in which communication burdens are significantly reduced as compared with those of existing consensus-based distributed control strategies. The proposed distributed control strategy improves the system operational flexibility and scalability for facilitating the integration of various DERs.

The remainder of this paper is organized as follows. Section II introduces centralized and consensus-based distributed control strategies for the economic operation of islanded MGs. Section III provides the detailed design of the proposed privacy-preserving distributed control strategy. Section IV demonstrates the optimality and the stability of the system equilibrium point using the Lyapunov theory. Section V presents extensive case studies and corresponding discussions. Finally, Section VI concludes this paper.

II. Economic Operation in Islanded MG

A. Centralized Control Strategy for MG ED Problem

Consider an islanded AC MG with N controllable inverter-based DERs operated in a grid-forming mode. These grid-forming DERs participate in the system frequency and voltage regulations while maintaining the system power balance to be satisfied. Instantaneous DER frequencies after disturbances would be different corresponding to respective disturbance locations [6],[18]. Thus, the communication network plays a vital role in coordinating the operations of participating DERs.

The objective of economic operation in an islanded MG is to minimize the total generation cost by dispatching available resources, where the MG system active power balance and DERs' maximum capacity constraints are considered. Thus, the economic dispatch (ED) of an islanded MG is formulated as:

$$\begin{aligned} &Min \quad \sum_{i=1}^{N} c_i\left(P_i\right) \\ &s.t. \quad \sum_{i=1}^{N} P_i = P_D \\ &\qquad P_{i,\min} \le P_i \le P_{i,\max} \end{aligned} \tag{1}$$

where P_D is the MG's total demand, which includes loads and MG network losses [12]. The generation cost function of participating DER is assumed to take a quadratic form as $c\left(P_i\right) = a_i P_i^2 + b_i P_i + c_i$ and the corresponding incremental cost is denoted by $\lambda_i = 2a_i P_i + b_i$ [10].

The Lagrangian function for ED problem (1) is stated as:

$$\begin{aligned} L = &\sum_{i=1}^{N} c_i\left(P_i\right) + \lambda\left(P_D - \sum_{i=1}^{N} P_i\right) \\ &+ \sum_{i=1}^{N} \overline{\mu}_i\left(P_i - P_{i,\max}\right) + \sum_{i=1}^{N} \underline{\mu}_i\left(P_{i,\min} - P_i\right) \end{aligned} \tag{2}$$

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In centralized control strategies, MC collects data from participating DERs, solves the optimization problem in (1), and broadcasts the optimal active power output set points to participating DERs. According to the first-order optimality conditions of the Lagrangian function in (2), EICC would be satisfied in the economic operation of MG, which is stated as:

$$\begin{cases} \lambda_i = \partial c_i\left(P_i\right)/\partial P_i = \lambda^*, P_{i,\min} < P_i < P_{i,\max} \\ \lambda_i = \partial c_i\left(P_i\right)/\partial P_i \le \lambda^*, P_i = P_{i,\max} \\ \lambda_i = \partial c_i\left(P_i\right)/\partial P_i \ge \lambda^*, P_i = P_{i,\min} \end{cases} \tag{3}$$

However, the centralized approaches have the following shortcomings: 1) MC faces significant communication and computation burdens to realize the real-time data collection and processing for a multitude of participating DERs; 2) Estimation of network losses and power imbalances might be imprecise, which would disrupt the real-time system power balance, especially when considering variable DERs and loads in islanded MGs; and 3) Preservation of participating DERs' privacy is violated since MC collects the data continuously.

B. Consensus-based Distributed Control Strategy for MG ED Problem

Using distributed control strategies, participating DERs in MG would communicate with their neighbors via a sparse communication network. Define $\mathbf{A} = \left(a_{ij}\right)_{N\times N}$ as the adjacency matrix, where $a_{ii} = 0$ and $a_{ij} = 1$ if and only if there is a communication link between DERs i and j. Define $\mathbf{D} = diag\left(d_1, ..., d_N\right)$ as the degree matrix, where $d_i = \sum_{j=1}^{N} a_{ij}$. The Laplacian matrix of communication network is stated as:

$$\mathbf{L} = \mathbf{D} - \mathbf{A} \tag{4}$$

According to the EICC stated in (3), if all DERs are operated within their capacity limits, their incremental costs are considered as consensus variables and the defined state error would be fed to an integral controller for generating the frequency set point adjustment for each DER. Then, the dynamics of frequency set point adjustment $u_{\omega i}$ are stated as:

$$\dot{u}_{\omega i} = e_i = -\sum_{j=1}^{N} a_{ij}\left(\lambda_i - \lambda_j\right) \tag{5}$$

Considering N DERs connected by the communication network, (5) is written in a matrix form stated in (6) for equalizing participating DERs' incremental costs.

$$\mathbf{e} = -\mathbf{L}\boldsymbol{\lambda} \tag{6}$$

The Laplacian matrix $\mathbf{L}$ is positive-semidefinite (i.e., $\lambda_i \ge 0, \forall i$) and irreducible (i.e., every participating DER is reachable by other DERs through the communication graph). Hence, the control protocol in (6) can drive participating DERs to reach consensus on incremental costs and the applied droop control for fast active power sharing would ensure the system power balance. Accordingly, the active power outputs of DERs operated at their capacity limits would be fixed and their frequency set points will not be updated [9]. These DERs would act as virtual links to interconnect their neighbors for ensuring the propagation of incremental cost information throughout the entire communication network. Compared to centralized control strategies, the consensus-based distributed control ones demonstrate high reliability and scalability, which are immune to single-point-failures [6]-[14].

However, the privacy-preserving problem is not well addressed in the existing distributed control strategies because participating DERs' generation data are still required to be shared with their neighbors via communication networks. Under such circumstances, generation data as sensitive private information might be abused by potential adversaries. Accordingly, we propose in this paper a privacy-preserving distributed control strategy for maintaining an MG's economic operation.

III. Privacy-Preserving Distributed Control Strategy for Economic Operation in Reconfigurable MG

In this section, a privacy-preserving distributed control strategy for an MG's economic operation is proposed in which only the frequency data are shared among participating DERs while DERs' generation data are privately-held. First, the detailed design of the proposed privacy-preserving distributed control strategy is presented. Second, the following two control objectives are demonstrated to be achieved: 1) Minimize the total generation cost while satisfying the system power balance constraint; 2) Restore DER frequencies to the rated value. Third, the implementation of the proposed distributed control strategy in reconfigurable MGs is discussed.

A. Proposed Distributed Control Strategy

In an islanded AC MG, the proposed distributed control strategy is designed as in (7), which is depicted in Fig. 1.

$$\begin{cases} \omega_i = \omega^{rated} - m_i\left(P_i - P_i^{rated}\right) + u_{\omega i} \\ \dot{u}_{\omega i} = -\beta v_i - \alpha\beta\sigma_i - \alpha\nabla f_i \\ v_i = \sum_{j=1}^{N} a_{ij}\left(\omega_i - \omega_j\right) + \left(\omega_i - \omega^{rated}\right) \\ \dot{\sigma}_i = \sum_{j=1}^{N} a_{ij}\left(\omega_i - \omega_j\right) \end{cases} \tag{7}$$

where $u_{\omega i}$ represents the designed control input for economic operation by adjusting the frequency set point of DER i. The control input is composed of three terms: 1) $-\beta v_i$ is the consensus term that synchronizes DER operating frequencies at the rated value; 2) $-\alpha\beta\sigma_i$ is the stability term that helps maintain the equilibrium point at the optimal point; 3) $-\alpha\nabla f_i$ is the optimization term in which each DER optimizes its privately-held local objective function. The proposed distributed control strategy drives participating DERs to the optimal operating point, in which the total generation cost is minimized and DER frequencies are restored to the rated value.

Each DER's local objective function is to minimize its generation cost while maintaining the system power balance. The droop control has a faster dynamic than that of the communication-based distributed control strategies [5]-[7]. Considering load variations, the primary control would quickly respond to restore the system power balance and then the communication-based distributed control coordinates the power sharing among participating DERs. Accordingly, the

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MG system's power imbalance can be estimated by $\int\left(\omega_i-\omega^{rated}\right)dt$, which is an integral function of frequency regulation using droop control. Thus, each DER's privately-held local objective function is formulated as:

$$f_i=\left(a_iP_i^2+b_iP_i+c_i\right)+\frac{\gamma_i}{2}\left(\int\left(\omega_i-\omega^{rated}\right)dt\right)^2 \tag{8}$$

And the derivative of the local objective function is simplified as:

$$\nabla f_i=2a_iP_i+b_i+\gamma_i\int\left(\omega_i-\omega^{rated}\right)dt \tag{9}$$

Thus, the proposed distributed control strategy, presented in Fig. 1(a), is viewed as fully distributed in which only the DER frequencies are shared among neighboring DERs and the generation data (i.e., local objective function) is held privately. Accordingly, the proposed distributed control strategy is considered privacy-preserving, where the communication burdens are also significantly reduced. Here, the utilized droop control of inverter-based DER is depicted in Fig. 1(b).

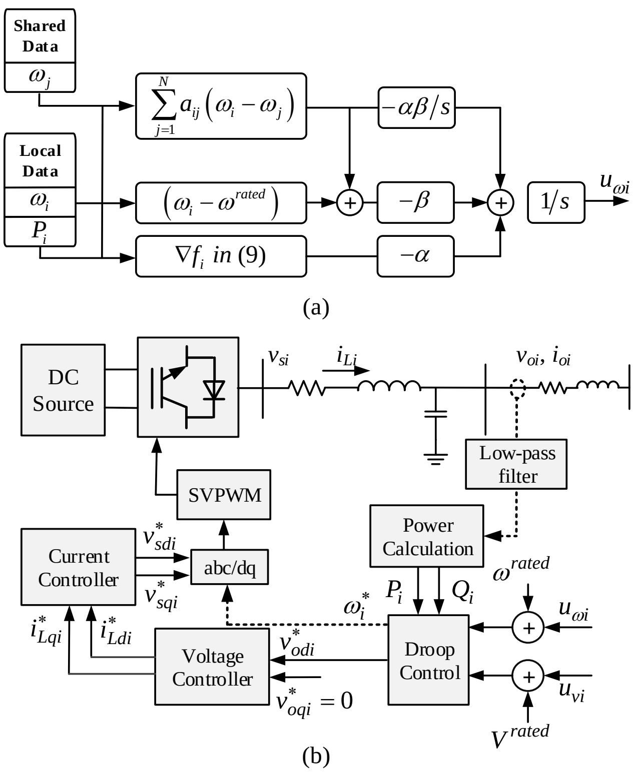

Fig. 1. (a) Proposed distributed control strategy; (b) Utilized droop control of DER.

B. Control Objectives in MG Economic Operation

Based on (7) and (9), the derivative of DER's frequency set point adjustment would decrease as the DER's incremental cost increases. Thus, frequency set points of DERs with higher incremental costs would decrease more significantly than those with lower incremental costs. The power balance constraint can be satisfied by integrating a positive term $\frac{\gamma_i}{2}\left(\int\left(\omega_i-\omega^{rated}\right)dt\right)^2$ to each DER's local objective function. After any disturbances, the active power outputs of DERs with higher incremental costs would decrease and those with lower incremental costs would increase until they all reach an equilibrium point. At this equilibrium point, participating DERs reach consensus on incremental costs and their frequencies are restored at the rated value.

Consider all participating DERs are operated within their maximum capacities. Assume that there is a system equilibrium point at which the DER frequencies are synchronized at the rated value while the participating DERs' incremental costs are different. The trends for DERs' active power outputs would be different since their optimization terms $-\alpha\nabla f_i$ are different. Thus, such a system equilibrium point cannot be stable and the assumption does not hold. Accordingly, equalizing participating DERs' incremental costs is demonstrated to be a necessary condition for the asymptotical stability of the MG system's equilibrium point with the proposed distributed control strategy. In the next section, the optimality and the asymptotical stability of the MG system's equilibrium point are demonstrated theoretically.

Using the proposed distributed control strategy, if a DER's active power output reaches its maximum capacity during power regulation, the DER should be maintained at its maximum capacity due to physical constraints. Such DERs would not update their frequency set points and relinquish the responsibilities of frequency regulations to their neighbors. In essence, such DERs would act as virtual links to interconnect their neighboring DERs for ensuring the functionality of the proposed distributed control strategy.

The utilization of communication network for connecting participating DERs would introduce communication delays. A comprehensive survey on communication delays in MGs is presented in [19]. The communication delays would postpone the convergence of MG system states, deteriorate the system dynamic performances, and even result in system instability [20],[21]. The theoretical analyses for the impacts of time delays on MG system stability are presented in [22]. If the communication delay exceeds the delay margin, there are several countermeasures to cope with communication delays for enhancing the MG system dynamic performance, including gain scheduling, predictive control, sliding mode control, and H_∞ control [19].

C. Implementation in Reconfigurable MG

Fig. 2 presents the illustrative structure of an islanded reconfigurable MG composed of three sub-MGs. The reconfigurable MG can have varying electrical and communication network topologies to manage available resources for ensuring reliable power services to local customers [15],[23]-[25]. Reconfiguration is an effective way to improve the power system performance, including reducing network losses [26], maximizing system loadability [27], optimizing voltage profile [28], isolating faulted areas [29],[30], enhancing system reliability and resilience [31]-[36].

MG network reconfiguration can effectively regulate local power flows to reduce network losses during the grid-connected operation and reduce load curtailments during the islanded operation [26]. When certain faults occur, effective and optimal reconfiguration can isolate system damages within certain areas and minimize the impacts of faults on the overall system performance [30]. However, the reconfigurations in MGs would change the equivalent

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impedances between participating DERs, which might lead a stable MG system to an unstable operation. The effect of reconfigurations on the small-signal stability margin of islanded MGs is theoretically analyzed in [37]. The reconfigurable structure provides additional operational flexibility and high fault tolerance for MG, which helps MG realize the benefits of allowing participating DERs to adapt to various operating conditions. Thus, the distributed control strategy should retain the cost-effective operational merits of reconfigurable MGs.

In existing distributed control strategies, designated communication networks are used for facilitating interactions among specific types of data [38]. For instance, the synchronization of DER frequencies and equalizing DERs' incremental costs are realized separately by using different communication networks with different convergence rates. Considering MG reconfiguration operations, the associated communication networks will be updated frequently while the corresponding impacts on the system convergence performance are not clear. Comparatively, using the proposed distributed control strategy, only frequency data will be shared among neighboring DERs while participating DERs' generation data are held privately as shown in Fig. 1. Since the system communication complexity is much reduced in the proposed method, the MG with the proposed distributed control strategy can further exploit DERs' plug-and-play capabilities and better adapt to changes in electrical and communication networks, which boosts the system operational flexibility for utilizing participating DERs more effectively.

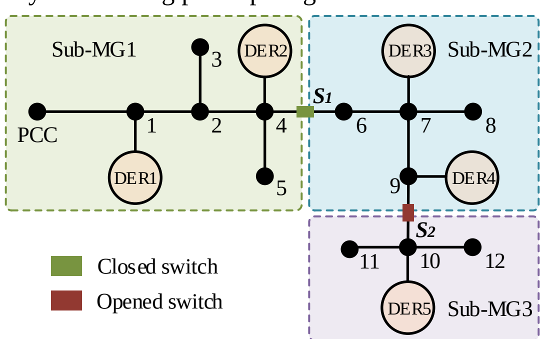

Fig. 2. Structure of an islanded reconfigurable MGs.

IV. Optimality and Stability Analyses of MG System Equilibrium Point

In this section, we will consider the optimality and asymptotical stability of the MG system equilibrium point. With the proposed distributed control strategy in (7), the MG system has an equilibrium point at which its objective function is optimized (i.e., the total generation cost is minimized and DER frequencies are synchronized at the rated value). In addition, it is demonstrated that the equilibrium point is globally asymptotical stable using the Lyapunov theory and Lasalle's Invariance Principle.

A. Optimality of MG System Equilibrium Point

In this subsection, we will demonstrate that the MG's objective function (i.e., the sum of DERs' local objective functions) is minimized at the equilibrium point, which indicates that the total generation cost is minimized and the MG system power balance constraint is satisfied.

Here, define $\boldsymbol{\omega} = \left[\omega_1, \omega_2, ..., \omega_N\right]^T$, $\boldsymbol{\sigma} = \left[\sigma_1, \sigma_2, ...\sigma_N\right]^T$, and $F(\boldsymbol{\omega}) = \sum_{i=1}^{N} f_i(\omega_i)$. The dynamics of the MG system is stated as:

$$\begin{cases} \dot{\boldsymbol{\omega}} = -\beta\left[\mathbf{L}\boldsymbol{\omega} + \left(\boldsymbol{\omega} - \boldsymbol{\omega}^{rated}\right)\right] - \boldsymbol{\sigma} - \alpha\nabla F(\boldsymbol{\omega}) \\ \dot{\boldsymbol{\sigma}} = \alpha\beta\mathbf{L}\boldsymbol{\omega}, \quad \boldsymbol{\sigma}(t_0) = 0 \end{cases} \tag{10}$$

where $\nabla F(\boldsymbol{\omega}) = \left[\nabla f_1(\omega_1), \nabla f_2(\omega_2), ..., \nabla f_N(\omega_N)\right]^T$.

Denote the MG system equilibrium point of (10) as

$$\begin{cases} \boldsymbol{\omega}^* = \left[\omega_1^*, \omega_2^*, ..., \omega_N^*\right]^T \\ \boldsymbol{\sigma}^* = \left[\sigma_1^*, \sigma_2^*, ..., \sigma_N^*\right]^T \end{cases} \tag{11}$$

In (7), the designed control signal $\dot{u}_{\omega i}$ is passed on to an integral controller and the output of the integral is the frequency set point adjustment for DER *i*. Then, it will hold that the control signal $\dot{u}_{\omega i}$ must be zero at steady state, which indicates that the equilibrium point in (11) would satisfy the following conditions:

$$\begin{cases} -\beta\left[\mathbf{L}\boldsymbol{\omega}^* + \left(\boldsymbol{\omega}^* - \boldsymbol{\omega}^{rated}\right)\right] - \boldsymbol{\sigma}^* - \alpha\nabla F\left(\boldsymbol{\omega}^*\right) = 0 \\ \alpha\beta\mathbf{L}\boldsymbol{\omega}^* = 0 \end{cases} \tag{12}$$

Define a *N*-dimensional column vector as $\mathbf{e}_N = (1, ..., 1)^T$. Since the matrix $\mathbf{L}$ is symmetric and $\mathbf{e}_N^T\mathbf{L} = 0$, we have

$$\sum_{i=1}^{N} \dot{\sigma}_i = \alpha\beta\mathbf{e}_N^T\mathbf{L}\boldsymbol{\omega} = 0 \tag{13}$$

Based on (13), we have

$$\sum_{i=1}^{N} \sigma_i(t) = \sum_{i=1}^{N} \sigma_i(t_0) = 0 \tag{14}$$

From (12), there is

$$-\boldsymbol{\sigma}^* - \alpha\nabla F\left(\boldsymbol{\omega}^*\right) = 0 \tag{15}$$

Multiplying the left side of (15) by $\mathbf{e}_N^T$, there is

$$\sum_{i=1}^{N} \sigma_i^* - \alpha\sum_{i=1}^{N} \nabla f_i\left(\omega_i^*\right) = 0 \tag{16}$$

Since the frequencies of DERs will be restored to the rated value (i.e., $\boldsymbol{\omega}^* - \boldsymbol{\omega}^{rated} = \mathbf{0}$), combining (14) and (16), there is

$$\sum_{i=1}^{N} \nabla f_i\left(\omega_i^*\right) = 0 \tag{17}$$

Accordingly, the optimality condition is satisfied and the equilibrium point in (11) is optimal, which indicates that the MG's objective function is minimized. In this way, the total generation cost is minimized while the system power balance is maintained.

B. Asymptotical Stability of MG System Equilibrium Point

In this subsection, we will demonstrate that the equilibrium point (11) is globally asymptotical stable. Consider the following Lyapunov function candidate.

$$V = \phi\left(-\beta\left[\mathbf{L}\boldsymbol{\omega} + \left(\boldsymbol{\omega} - \boldsymbol{\omega}^{rated}\right)\right] - \boldsymbol{\sigma} - \alpha\nabla F(\boldsymbol{\omega})\right) + \frac{1}{2}\alpha\beta\boldsymbol{\omega}^T\mathbf{L}\boldsymbol{\omega} \tag{18}$$

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where $\phi(s)$ is defined as $\phi(s)=\int_0^s tdt \geq 0$. Thus, the Lyapunov function defined in (18) satisfies $V \geq 0$.

The time derivative of the Lyapunov function candidate in (18) is stated as:

$$\begin{aligned}\dot{V} &= -\beta\mathbf{u}^T\mathbf{L}\mathbf{u}-\mathbf{u}^T\mathbf{u}-\mathbf{u}^T\left(\alpha\beta\mathbf{L}\boldsymbol{\omega}\right)-\alpha\mathbf{u}^T\nabla^2F\left(\boldsymbol{\omega}\right)\mathbf{u}+\alpha\beta\boldsymbol{\omega}^T\mathbf{L}\mathbf{u}\\ &= -\beta\mathbf{u}^T\mathbf{L}\mathbf{u}-\mathbf{u}^T\mathbf{u}-\alpha\mathbf{u}^T\nabla^2F\left(\boldsymbol{\omega}\right)\mathbf{u}\\ &\leq -\alpha\mathbf{u}^T\nabla^2F\left(\boldsymbol{\omega}\right)\mathbf{u}\\ &= -\alpha\left(-\beta\left[\mathbf{L}\boldsymbol{\omega}+\left(\boldsymbol{\omega}-\boldsymbol{\omega}^{rated}\right)\right]-\boldsymbol{\sigma}-\alpha\nabla F\left(\boldsymbol{\omega}\right)\right)\nabla^2F\left(\boldsymbol{\omega}\right)\\ &\quad\left(-\beta\left[\mathbf{L}\boldsymbol{\omega}+\left(\boldsymbol{\omega}-\boldsymbol{\omega}^{rated}\right)\right]-\boldsymbol{\sigma}-\alpha\nabla F\left(\boldsymbol{\omega}\right)\right)\end{aligned} \tag{19}$$

where $\nabla^2F\left(\boldsymbol{\omega}\right)=diag\left(\nabla^2 f_1\left(\omega_1\right),\nabla^2 f_2\left(\omega_2\right),\ldots,\nabla^2 f_N\left(\omega_N\right)\right)$ and $\mathbf{u}$ is defined as $\mathbf{u}=-\beta\left[\mathbf{L}\boldsymbol{\omega}+\left(\boldsymbol{\omega}-\boldsymbol{\omega}^{rated}\right)\right]-\boldsymbol{\sigma}-\alpha\nabla F\left(\boldsymbol{\omega}\right)$.

Since the optimization term is strictly convex, we have $\nabla^2F\left(\boldsymbol{\omega}\right)>0$. It holds that $\dot{V}\leq 0$ and $\dot{V}=0$ if and only if

$$-\beta\left[\mathbf{L}\boldsymbol{\omega}+\left(\boldsymbol{\omega}-\boldsymbol{\omega}^{rated}\right)\right]-\boldsymbol{\sigma}-\alpha\nabla F\left(\boldsymbol{\omega}\right)=0 \tag{20}$$

The time derivative of (20) can be stated as:

$$\begin{aligned}&-\beta\mathbf{L}\left(-\beta\left[\mathbf{L}\boldsymbol{\omega}+\left(\boldsymbol{\omega}-\boldsymbol{\omega}^{rated}\right)\right]-\boldsymbol{\sigma}-\alpha\nabla F\left(\boldsymbol{\omega}\right)\right)\\ &-\beta\left(-\beta\left[\mathbf{L}\boldsymbol{\omega}+\left(\boldsymbol{\omega}-\boldsymbol{\omega}^{rated}\right)\right]-\boldsymbol{\sigma}-\alpha\nabla F\left(\boldsymbol{\omega}\right)\right)\\ &-\alpha\beta\mathbf{L}\boldsymbol{\omega}-\alpha\nabla F^2\left(\boldsymbol{\omega}\right)\left(-\beta\left[\mathbf{L}\boldsymbol{\omega}+\left(\boldsymbol{\omega}-\boldsymbol{\omega}^{rated}\right)\right]-\boldsymbol{\sigma}-\alpha\nabla F\left(\boldsymbol{\omega}\right)\right)\\ &=-\alpha\beta\mathbf{L}\boldsymbol{\omega}=0\end{aligned} \tag{21}$$

Based on (19)-(21), the two conditions stated in (12) are satisfied in the system equilibrium point, which indicates that the MG system in (10) is stable ($\dot{V}=0$) if and only if it reaches the equilibrium point. The system equilibrium point in (11) is demonstrated to be globally asymptotical stable based on Lasalle's Invariance Principle [39].

In summary, the optimality and the stability of the MG system equilibrium point are demonstrated theoretically. Accordingly, the MG system with the proposed distributed control strategy has a system equilibrium point at which the MG's objective function is optimized, and the equilibrium point is also globally asymptotical stable. Then, the MG system's optimal economic operation and frequency restoration are achieved simultaneously.

V. Case Studies

The effectiveness of the proposed distributed control strategy is validated in a 12-bus MG system using time-domain PSCAD/EMTDC simulations [15]. In Fig. 3, the test system contains five DERs (located at Buses 1, 4, 7, 9, and 10, respectively), five loads (located at Buses 3, 5, 6, 8, and 11, respectively) and two switches (i.e., *S1* and *S2*). The reconfigurable MG system has varying electrical network topologies by regulating the operation of the two switches. The line impedances are set identical (i.e., $0.2\Omega + 1\text{mH}$) to simplify the modeling of the system. The effect of line impedance on system stability has been analyzed theoretically in [37]. Fig. 4 depicts the communication network connecting the five DERs. The parameters of the five DERs are presented in Table I.

The detailed model of inverter-based DERs and the design of droop control coefficients have been discussed in [40],[41]. When the droop coefficients are small, the dominant eigenvalues are far from the imaginary axis while the system dynamic response is relatively slow and steady state errors might exist. With an increase in droop coefficients, the system dynamic response would be accelerated. However, the dominant eigenvalues would gradually move away from the real axis, which implies that the system dynamic performance might exhibit oscillatory behaviors. Also, the dominant eigenvalues would move closer to the imaginary axis, which implies that the larger droop coefficients might deteriorate the system stability.

The following three case studies are conducted:

1) Load variations;
2) DER disconnection and reconnection operations;
3) MG reconfiguration operations.

These three cases are discussed next.

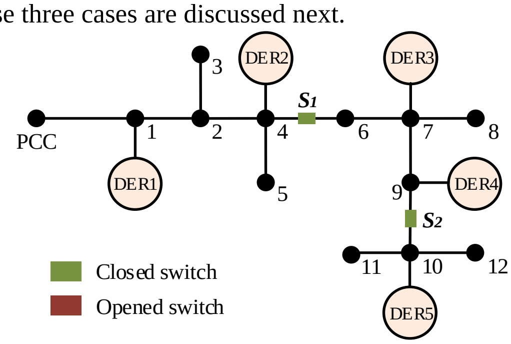

Fig. 3. 12-bus reconfigurable MG system.

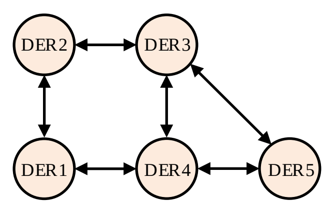

Fig. 4. Communication network of the 12-bus MG system.

TABLE I
DER PARAMETERS IN 12-BUS MG SYSTEM

Unit	Bus	a_i (\$/kW²h)	b_i (\$/kWh)	c_i (\$/h)	m_i (Hz/kW)
DER1	1	0.001	0.070	1.00	0.02
DER2	4	0.001	0.070	1.50	0.02
DER3	7	0.001	0.085	2.00	0.02
DER4	9	0.0005	0.085	3.00	0.02
DER5	10	0.0005	0.100	4.00	0.02

A. Load Variations

The performance of the proposed distributed control strategy in case of load variations is presented in Fig. 5. The MG system starts to operate in islanded mode at t=0s and the two switches (i.e., *S2* and *S2*) are kept closed throughout the simulation time.

Initially, the total system load is proportionally shared among the five DERs within the MG system, as shown in Fig. 5(a). Later, the proposed distributed control strategy is activated at t=10s. In Fig. 5(b), the active power outputs of the five DERs are readjusted and their incremental costs are regulated to be identical, implying that the MG economic operation is realized. With the proposed distributed control strategy in (7), the optimization term leads to a slight drop in DER frequencies at first and then the consensus term would restore the DER frequencies to 60Hz, as shown in Fig. 5(c).

An additional load (90kW+j10kVar) is added to Bus 7 at t=20s and removed at t=30s. The active power outputs of the five DERs are readjusted to mitigate the MG system power imbalance as their frequencies deviate from the rated value. With the proposed distributed control strategy, the incremental costs of the five DERs are gradually adjusted to be identical and their frequencies are restored to 60Hz, as shown in Fig. 5. Accordingly, the MG system maintains an economic operation regardless of load variations. Fig. 6 shows that the proposed distributed control strategy can still maintain the MG economic operation with communication delay set as 0.2s. Due to communication delays, the corresponding convergence rate in Fig. 6 is reduced as compared to that in Fig. 5.

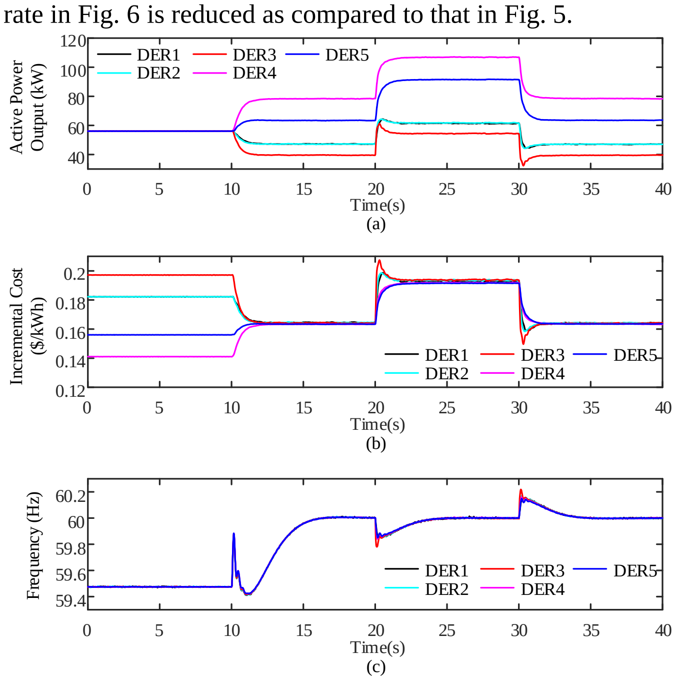

Fig. 5. Performance of the proposed distributed control strategy for load variations: (a) Active power output; (b) Incremental cost; (c) Frequency.

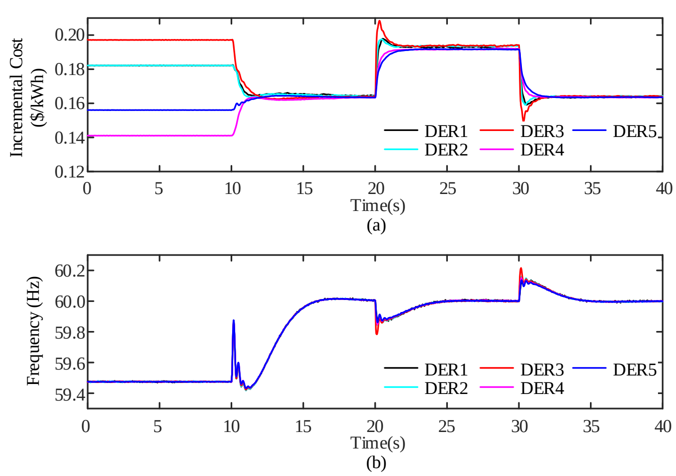

Fig. 6. Performance of the proposed distributed control strategy for load variations with communication delay set as 0.2s: (a) Incremental cost; (b) Frequency.

In Fig. 7, the versatility of the proposed distributed control strategy is also tested. Here, the DER incremental cost $\lambda_i = 2a_i P_i + b_i$ in the optimization term (9) is modified as $m_i P_i$, which indicates that the control objective is updated to achieve proportional active power sharing among participating DERs. After the proposed distributed control strategy is activated at t=10s, DER frequencies are restored to 60Hz. Due to the frequency restoration, frequency-dependent loads are slightly increased and then the active power outputs of the five DERs are increased correspondingly, while the proportional active power sharing is maintained among participating DERs. Later, an additional load (90kW+j10kVar) is added to Bus 7 at t=20s and removed at t=30s. In Fig. 7, the proportional active power sharing is restored among participating DERs within 3s after the load change while the DER frequencies are restored to 60Hz. The scenario implies that the proposed distributed control strategy can be extended to satisfy various control objectives by just modifying the optimization term while without requiring any additional communication and control infrastructures.

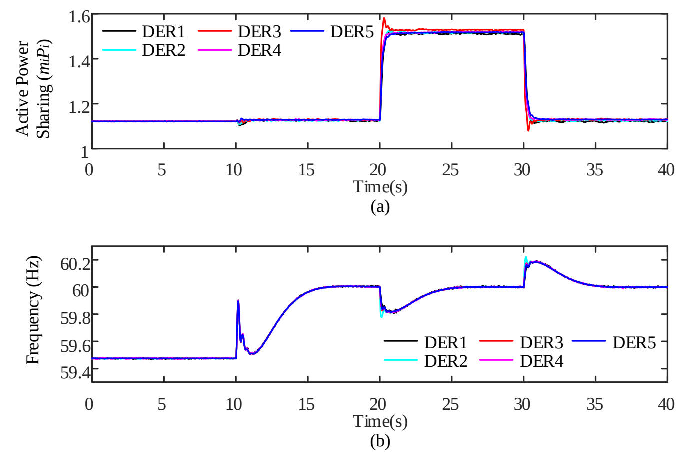

Fig. 7. Performance of the proposed distributed control strategy for proportional active power sharing: (a) Active power sharing; (b) Frequency.

B. Disconnection and Reconnection Operations of DERs

The performance of the proposed distributed control strategy for DER disconnection and reconnection operations is presented in Fig. 8. After the proposed distributed control strategy is activated at t=10s, DER1 and DER5 are disconnected from Bus 1 and Bus 10 at t=20s and t=30s, respectively. In Fig. 8, the remaining DERs would increase their active power outputs to mitigate the power imbalance. Accordingly, their incremental costs are increased with the increased active power outputs while satisfying the EICC. The remaining DER frequencies are also stabilized at 60Hz.

Later, DER5 and DER1 are reconnected to Bus 10 and Bus 1 at t=40s and t=50s, respectively, and the MG system load is shared among participating DERs again. The proposed distributed control strategy will drive the incremental costs of the participating DERs to be identical while satisfying the system power balance constraint and maintaining their frequencies at the rated value. In Fig. 8, the desired control performance is realized within 5s after DERs' disconnection and reconnection operations. Accordingly, the MG system's economic operation can be maintained using the proposed distributed control strategy in the presence of disconnection and reconnection operations of DERs. Thus, the proposed

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPWRS.2020.2985995, IEEE Transactions on Power Systems

distributed control strategy offers a plug-and-play feature for participating DERs, which enhances the MG system scalability for accommodating various DERs.

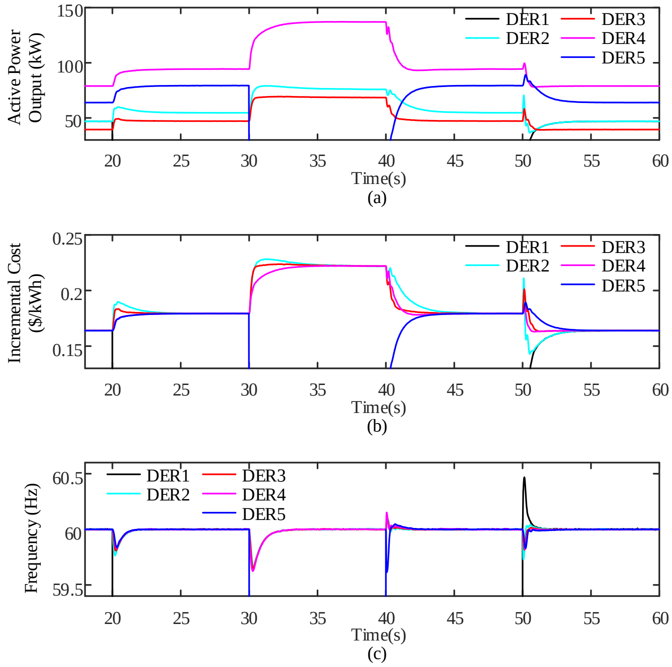

Fig. 8. Performance of the proposed distributed control strategy for DER disconnection and reconnection operations: (a) Active power output; (b) Incremental cost; (c) Frequency.

C. MG Reconfiguration Operations

In this case, the initial conditions are the same as those in the previous two cases. The MG system starts to operate in islanded mode with two closed switches at t=0s, and the proposed distributed control strategy is activated at t=10s. In Fig. 9, four reconfiguration operations are conducted successively by regulating the two switches. The performance of the proposed distributed control strategy for the MG reconfiguration operations is presented in Fig. 10.

At t=20s, the switch *S1* is opened and the MG is divided into two sub-MGs, where DERs 1 and 2 are in one sub-MG and DERs 3, 4 and 5 are in the other sub-MG. In Fig. 9, the MG system is reconfigured from topology (I) to (II). The power balance in the two sub-MGs is interrupted by the opening of *S1*. DERs 1 and 2 readjust their active power outputs to mitigate the power imbalance in the sub-MG. With the proposed distributed control strategy, the incremental costs of DERs 1 and 2 are regulated to be identical while their frequencies are stabilized at 60Hz, as shown in Fig. 10. A similar performance is presented for DERs 3, 4, and 5, as shown in Fig. 10. Thus, the economic operations of the two sub-MGs are realized separately and the DER frequencies are stabilized at the rated 60Hz.

At t=30s, the switch *S2* is opened and the MG system is reconfigured from topology (II) to (III), as shown in Fig. 9. Then, the loads located at Buses 3 and 5 are only supplied by DERs 1 and 2, the loads located at Buses 6 and 8 are supplied by DERs 3 and 4, and the load located at Bus 11 is supplied by DER 5. In each sub-MG, the DERs' incremental costs are regulated to be identical, implying that the economic operation of each sub-MG is realized. At t=40s, the switch *S1* is closed and the MG system is reconfigured from topology (III) to (IV), as shown in Fig. 9. With the proposed distributed control strategy, the incremental costs of DERs belonging to the same sub-MG are regulated to be identical, as shown in Fig. 10.

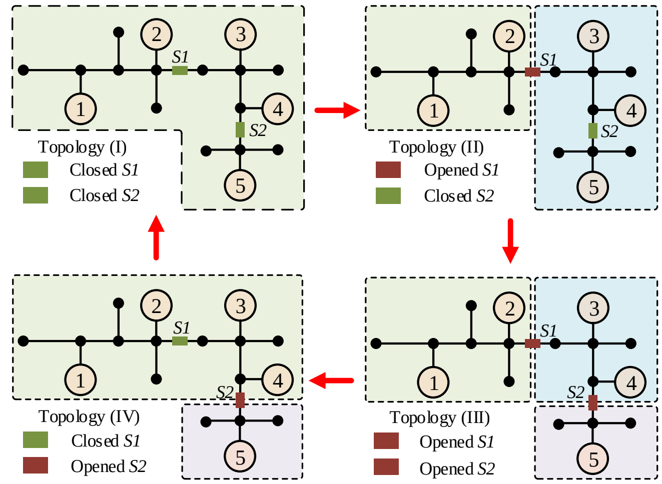

Fig. 9. Network topologies corresponding to MG system reconfiguration operations.

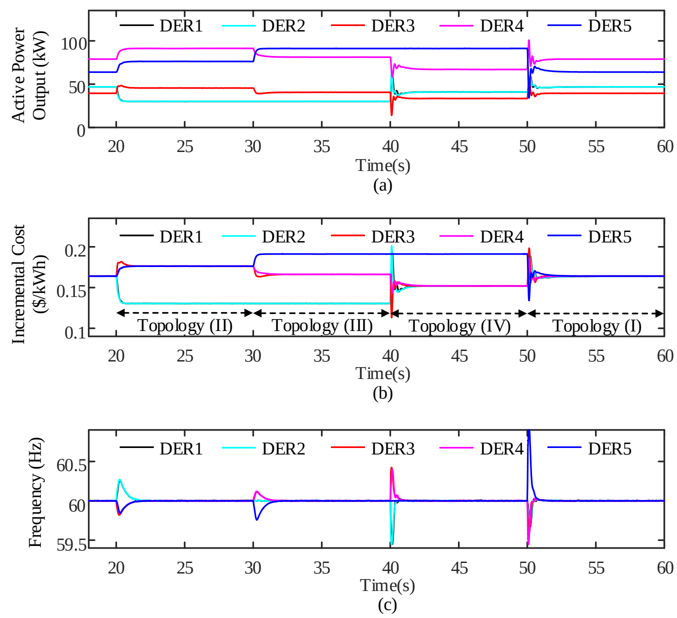

Fig. 10. Performance of the proposed distributed control strategy for MG reconfigurations: (a) Active power output; (b) Incremental cost; (c) Frequency.

Finally, the switch *S2* is closed, and the MG system is reconfigured from topology (IV) back to (I) at t=50s. In Fig. 10, the incremental costs of the five DERs are regulated to be identical and their frequencies are still stabilized at the rated 60Hz. Therefore, the proposed distributed control strategy is always functional in the presence of MG reconfiguration operations, which retains the operational flexibility of reconfigurable MGs for utilizing participating DERs' benefits more effectively.

Using the proposed distributed control strategy, only the frequency data are shared among participating DERs while each participant's generation data are held privately, implying that participants' privacy is preserved and the corresponding communication burdens are significantly reduced. In Figs. 5, 8, and 10, the optimal power sharing among participating DERs is achieved while restoring DER frequencies at the rated value for various operating conditions, including load variations, DER disconnection and reconnection operations, and MG reconfiguration operations.

VI. Conclusions

A privacy-preserving distributed control strategy is proposed for the economic operation of an islanded reconfigurable MG. With the increasing penetration of DERs, the infrastructure cost and the complexity of communication networks would increase significantly. Using the proposed distributed control strategy, only the frequency data would be shared among participating DERs via the communication network while the generation data are privately held by each participant. Compared with the existing distributed control strategies, the proposed distributed control strategy features the following three advantages: 1) Preserving the privacy of participating DERs; 2) Enhancing the MG system scalability by reducing the corresponding communication system complexities; 3) Exploiting the flexibility in reconfigurable MGs by helping MGs adapt to changes in electrical and communication network topologies.

The presented case studies validate that the proposed distributed control strategy can achieve optimal power sharing and frequency restoration under various operating conditions, i.e., load variations, DER disconnection and reconnection operations, and MG reconfiguration operations. A distributed strategy is considered for the real-time economic operation of reconfigurable MGs, which further enhances the MG system's operational flexibility for realizing the benefits of variable DERs more effectively. The proposed distributed control strategy exploits the operational merits of reconfigurable MGs, which offers opportunities to accommodate various DERs, adapts to changing operating conditions, and promotes the development of smart MG-based distribution networks.

VII. Acknowledgement

The Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah, funded this project, under grant no. (RG-10-135-41).

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