A Zeno-Free Distributed Self-Triggered Secondary Control Scheme for Islanded Microgrids

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***Abstract*—Distributed secondary control of microgrids is usually based on continuous-time-based control and communication assumption, which is neither economical nor efficient. In this paper, a distributed self-triggered control strategy is proposed based on the signum function to reduce the computation and communication requirements. With the self-triggered distributed controller, each DG only makes decision and propagates information to its neighbors at the specific event times, rather than continuously. To monitor the events, a linear clock is established according to the local consensus error and a preset convergence error, and hence the controller can exclude Zeno behavior naturally. By implementing the self-triggered distributed control for active power sharing and implementing a local frequency restoration control, the secondary control of islanded microgrids can be achieved distributedly with very less control actions and communications. Simulation results illustrate the validation of the proposed control scheme.**

***Index Terms*—Microgrid, distributed control, secondary control, self-triggered mechanism, Zeno-freeness**

I. Introduction

Microgrid (MG) is a promising way to facilitate the utilization of the renewable energy due to its operation flexibility, which is important to reduce carbon emissions and improve power supply reliability [1]. One of the advantages of MGs is that they can operate in islanded mode, i.e., they can operate alone without connecting the main grid. Therefore, the control system is essential for MGs to provide flexibility.

Typically, the hierarchical control structure is used as a preferred way to construct the control system in MGs [2], [3]. The hierarchical control structure includes three control levels, namely the primary, secondary, and tertiary control. The primary control is responsible for stabilizing the frequency and voltage of MGs after disturbances occurring in the shortest time scale. It is usually implemented by the droop control algorithm. But the droop mechanism can cause frequency and voltage deviations after the regulation. The secondary control is devoted to compensate the deviations caused by the primary control, and is also responsible for achieving accurate power sharing among the distributed generators (DGs) with a longer time scale. The tertiary control is in charge of the economical dispatch and optimal operation of the overall system, which operates with the longest time scale.

In this paper, we focus on the secondary control of MGs. The secondary control in MGs can be implemented by the centralized control structure. But this structure suffers from the single point of failure and has poor scalability. Hence, it is not suitable for the MGs with a large number of distributed generators (DGs) connected. Therefore, the multi-agent system-based distributed secondary control, which has better reliability and scalability, is regarded as the preferred control scheme and has been widely investigated. There have been many distributed secondary control strategies being reported in the literature [4]–[9]. But, most of them are based on the continuous-time-based control and communication assumption, which is neither economical nor efficient since the assumption could lead to a wasteful usage of the communication and computing resources.

In fact, the distributed secondary control can be achieved with less control actions and communications. That is the control action and communication can be conducted only when necessary. This kind of scheme is referred to as distributed event-triggered control, which can reduce the requirement of control action and communication significantly. Many researchers have devoted to designing distributed event-triggered

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controllers to solve the secondary control of frequency restoration or power sharing problem with less communications [10]–[13]. However, most of the event-triggered controllers require monitoring of the triggering condition continuously, which would increase the computation burden in turn. To overcome this deficiency, some researchers derived the upper bound of the triggering condition checking period of the event-triggered control to enlarge the period of checking [13], and hence further reduce the computation burden. Another way to address this problem is to design distributed self-triggered mechanism for the secondary control. In this way, the controller determines the next triggering time according to the local and neighboring states at previous triggering time instants [14], [15]. To the best of the authors' knowledge, the research on the distributed self-triggered secondary control in islanded MGs is insufficient. One of the few relevant studies is the distributed self-triggered power sharing control [16] using the self-triggered mechanism proposed in [14]. But the computing of the time interval for deriving the next triggering time is rather complicated, which would also increase the computing burden in the other aspect. Thus, how to design an effective distributed self-triggered secondary control motivates our research of this paper.

In this paper, a distributed self-triggered secondary control strategy is proposed based on the signum function. The contributions of this paper lie in: We design a distributed self-triggered mechanism for power sharing control by establishing a linear clock to monitor the triggering times. The linear clock is determined by the maximum of the local consensus error and a preset convergence error, which is easy to implement and does not involve triggering condition computing. With this clock, the controller can naturally exclude Zeno behavior. Then, by conducting the frequency restoration control locally, the secondary control can be achieved distributedly with very less control actions and communications. Theoretical analysis and simulation results validate the correctness and effectiveness of the proposed method.

The remainder of this paper is organized as follows: In Section II, the control systems in islanded MGs are introduced briefly. In Section III, the main work of this paper regarding the distributed self-triggered secondary control algorithm is proposed. Then, Section IV provides the verification study of the proposed control scheme. Finally, Section V concludes our work in this paper.

II. The Control Systems in Islanded Microgrids

In this section, we will briefly introduce the control systems in islanded microgrids, including the model of inverter-based DGs, the droop-based primary control and the distributed secondary control.

A. The Model of Inverter-Based DGs

In MGs, the distributed renewable energy resources can be modeled as inverter-based DGs, each of which is consist of a DC resource, a DC/AC inverter and a LC filter. To generate desired power output, the inverter-based DG is regulated by PWM control, inner current control and inner voltage control in a cascading configuration. The control structure of an inverter-based DG is illustrated in Fig. 1. It should be note that, the inner control loops in the inverter-based DGs have very short time scales, and hence are always neglect when considering the secondary control. Therefore, we will not introduce the specific dynamics of the inner control loops in this paper due to the space limitation. One can refer to [17] for the detailed dynamics of these control loops.

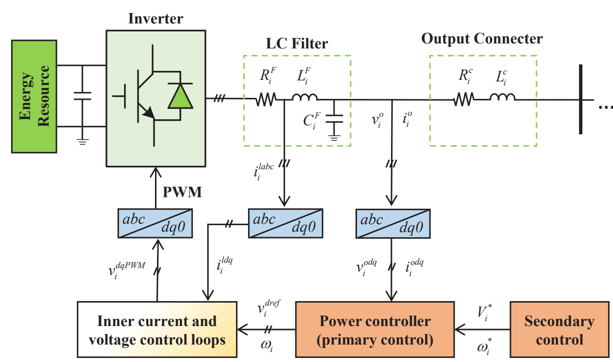

Fig. 1. The control structure of an inverter-based DG

B. The Droop-Based Primary Control

The inner current and voltage control loops require for the primary control to provide references. Typically, in MGs, the primary control of a DG is realized by the droop mechanism which mimics the operation of the traditional synchronous generator. The droop mechanism of a DG characterizes the relationship between the frequency and the active power output, and the relationship between the voltage and the reactive power output, which can be given as follows:

$$\begin{cases} \omega_i = \omega_i^* - m_i P_i \\ V_i = V_i^* - n_i Q_i, \end{cases} \tag{1}$$

where ω_i and V_i are the angular frequency and the voltage magnitude of the DG. ω_i^* and V_i^* are the references for the droop control regulated by the secondary control. m_i and n_i are the droop coefficients for angular frequency and voltage, respectively. P_i and Q_i are the active and reactive power at the DG's terminal.

It is noteworthy that the droop-based primary control is a kind of local control that only employs local information without involving any communications.

By the droop-based primary control, the frequency and the voltage of MGs can be stabilized quickly after disturbances occurring, such as load or generation changes. However, the droop mechanism could lead to frequency and voltage deviations after regulation, which would reduce the reliability and resilience of the MG operating in islanded mode. Thus, the secondary control is required to compensate the deviations of frequency and voltage caused by the droop-based primary control.

C. The Distributed Secondary Control

Traditionally, centralized secondary control needs a control center to collect the global information and make decisions. Thus, a star communication network is mandated to connect the control center with each DG. But, this structure suffers from single point of failure and has poor scalability. Different from the centralized control structure, the distributed control only requires each DG to conduct local control and neighboring communication, then the global objective can be achieved. Therefore, the secondary control with distributed control structure has better reliability and scalability.

The communication network is important for the distributed secondary control. It is in general represented by a undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of nodes representing the set of DGs, $\mathcal{E}$ is the set of edges indicating the communication links between DGs. If DG i can recieve information from DG j, then $(i, j) \in \mathcal{E}$. Thus, DG j is called the neighbor of DG i. Note that $(i, j) \in \mathcal{E}$ implies $(j, i) \in \mathcal{E}$ in a undirected graph. We denote by $\mathcal{N}_i$ the neighbor set of DG i. The communication network can be formulated by an adjacency matrix $A = [a_{ij}]$ with proper dimension, where $a_{ij} = 1$ if $(i, j) \in \mathcal{E}$, otherwise $a_{ij} = 0$. Denote $D = \text{diag}\{|\mathcal{N}_i|\}$ by the degree matrix of $\mathcal{G}$, in which $|\mathcal{N}_i|$ is the cardinality number of $\mathcal{N}_i$, indicating the number of DG i's neighbors. Then, the Laplacian matrix L is defined by $L = D - A$.

For the secondary control objectives, we focus on the accurate active power sharing and frequency restoration control objectives in this paper. To achieve accurate power sharing, the authors in [4] proposed a distributed controller to realize fair utilization profile of each DG by using consensus algorithm. By fair utilization profile, it means, in a MG, each DG plays an equal role to support the stable operation of the system, which can be given by

$$\frac{P_1}{P_1^{\max}} = \frac{P_2}{P_2^{\max}} = \cdots = \frac{P_N}{P_N^{\max}}, \tag{2}$$

where $P_i^{\max}$ is the maximum output of DG i.

To achieve (2), the following distributed control law for DG i is usually employed.

$$u_{P_i} = -k_P \sum_{j \in \mathcal{N}_i} a_{ij}(p_i - p_j). \tag{3}$$

where $k_P > 0$ is the coupling gain; $p_i = P_i / P_i^{\max}$.

For frequency restoration control, most of the existing work employ the leader-follower consensus algorithm to achieve the objective distributedly [6], [17]. However, for islanded MGs, the top priority task is to maintain the stable operation with high power quality. Thus, the nominal frequency value, i.e., 50 Hz, for the system should be satisfied as much as possible. Therefore, we can safely assume that each DG knows the nominal value when the MG operates in islanded mode. Thus, we can use simple PI control to achieve frequency restoration locally, specifically,

$$u_{\omega_i} = k_\omega^p(\omega^r - \omega_i) + k_\omega^I \int (\omega^r - \omega_i)\text{d}t. \tag{4}$$

By using (3) and (4), the secondary control objectives

$$\lim_{t \to \infty} |\omega_i - \omega^r| = 0. \tag{5}$$

and

$$\lim_{t \to \infty} |\frac{P_i}{P_i^{\max}} - \frac{P_j}{P_j^{\max}}| = 0. \tag{6}$$

can be realized by regulating the droop-based primary control as follow:

$$\omega_i = \omega_i^* + u_{\omega_i} + u_{P_i} - m_i P_i. \tag{7}$$

However, it is worth pointing out that the traditional distributed power sharing control (3) is based on the assumption of continuous-time-based control and communication, which leads to a wasteful use of computation and communication resources. To overcome this disadvantage, a distributed self-triggered secondary control is developed in the following section.

III. Distributed Self-Triggered Secondary Control

In this section, a Zeno-free distributed self-triggered power sharing control algorithm is designed based on a designed linear clock. And its theoretical correctness is provided by considering the Lyapunov stability of the controller.

A. Zeno-Free Distributed Self-Triggered Power Sharing Controller Design

We first define the following consensus error for the sake of notation brevity,

$$\text{con}_i(t) = \sum_{j \in \mathcal{N}_i} a_{ij}(p_i(t) - p_j(t)). \tag{8}$$

Then, by using the following function

$$\text{sign}_\varepsilon(x) \begin{cases} \text{sign}(x) & \text{if } |x| \geq \varepsilon \\ 0 & \text{otherwise,} \end{cases} \tag{9}$$

in which $\varepsilon > 0$ is the desired error, the distributed self-triggered power sharing control input for $\dot{p}_i(t) = u_{P_i}(t)$ is designed as follows

$$\begin{cases} u_{P_i}(t) = -\text{sign}_\varepsilon(\widehat{\text{con}}_i(t)) \\ \dot{\theta}_i(t) = -1, \end{cases} \tag{10}$$

where

$$\widehat{\text{con}}_i(t) = \text{con}_i(t_k^i) \text{ for } t \in [t_k^i, t_{k+1}^i), \tag{11}$$

in which t_k^i is the k-th ($k = 1, 2, \cdots$) triggering time instant of DG i defined by

$$t_k^i = \inf\{t > t_{k-1}^i | \theta_i(t) = 0\}. \tag{12}$$

The $\theta_i(t)$ is a linear clock with the dynamic of $\dot{\theta}_i(t) = -1$ for DG i, which satisfies the following evolution

$$\theta_i(t^+) = \begin{cases} \max\{\frac{|\mathrm{con}_i(t)|}{4|\mathcal{N}_i|}, \frac{\varepsilon}{4|\mathcal{N}_i|}\} & \text{if } \theta_i(t) = 0 \\ \theta_i(t) & \text{otherwise.} \end{cases} \quad (13)$$

The principle behind this controller design is as follows: (11) indicates that the controller input u_{P_i} is updated by $\mathrm{con}_i(t)$ only at the triggering time instant, i.e., $t = t_k^i$, otherwise, u_{P_i} remains unchangeable during the event time interval $[t_k^i, t_{k+1}^i)$. The clock variable $\theta_i(t)$ is designed to monitor the triggering time instants, which decays linearly since $\dot{\theta}_i(t) = -1$. Thus, (12) and (13) imply that when $\theta_i(t)$ decays to zero, the time is defined as the triggering time instant, in the meanwhile, $\theta_i(t)$ is updated by $\max\{\frac{|\mathrm{con}_i(t)|}{4|\mathcal{N}_i|}, \frac{\varepsilon}{4|\mathcal{N}_i|}\}$. The evolution process of θ_i can be illustrated by Fig. 2.

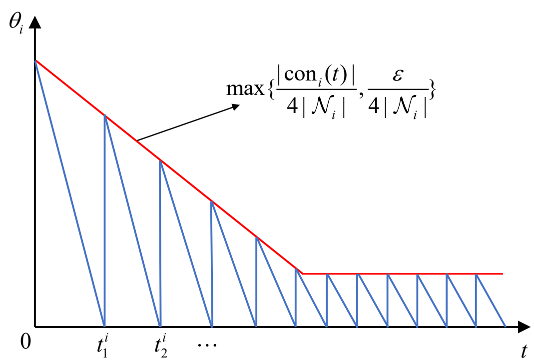

Fig. 2. The evolution process of θ_i

It is worth remarking that the evolution of θ_i naturally define the event times of DG i, namely,

$$t_{k+1}^i = t_k^i + \begin{cases} \frac{|\widehat{\mathrm{con}}_i(t_k^i)|}{4|\mathcal{N}_i|} & \text{if } |\mathrm{con}_i(t_k^i)| \geq \varepsilon \\ \frac{\varepsilon}{4|\mathcal{N}_i|} & \text{if } |\mathrm{con}_i(t_k^i)| < \varepsilon. \end{cases} \quad (14)$$

Thus, we immediately argue that, for each DG i, the time interval between every two adjacent triggering time instants has a lower bound: for any $k \geq 1$

$$t_{k+1}^i - t_k^i \geq \frac{\varepsilon}{4|\mathcal{N}_{\max}|}. \quad (15)$$

where $|\mathcal{N}_{\max}| = \max\{|\mathcal{N}_i|\}$. This means that the self-triggered controller can naturally exclude Zeno behavior.

It is also worthy of noting that, with the linear clock, there is no need for the controller to continuously calculating a triggering condition function as the event-triggered controller does [11]. This can greatly reduce the computation requirement for each DG.

Then, we give Theorem 1 to state the convergence result.

Theorem 1: For a MG with N DGs, which communicate with each other under an undirected and connected network, if each DG is equipped with the designed controller (10), whose triggers are monitored by (12) and (13). Then, by choosing a proper ε, the power sharing control objective can be achieved as follow:

$$\lim_{t\to\infty} |\sum_{j\in\mathcal{N}_i} (\frac{P_i}{P_i^{\max}} - \frac{P_j}{P_j^{\max}})| \leq \varepsilon. \quad (16)$$

The proof of Theorem 1 is provided in the following subsection.

B. Controller Stability Analysis

The proof of Theorem 1: For $t \geq 0$, consider the candidate Lyapunov function

$$V(t) = \frac{1}{2} p^T(t) L p(t) > 0. \quad (17)$$

where $p(t) = [p_1(t), p_2(t), \cdots, p_N(t)]^T$.

Then we consider the evolution of the derivative of $V(t)$. Since L is symmetric, we can derive

$$\begin{aligned} \dot{V}(t) &= p^T(t) L \dot{p}(t) = p^T(t) L u_P(t) = u_P^T(t) L p(t) \\ &= -\sum_{i=1}^{N} [\sum_{j\in\mathcal{N}_i} (p_i(t) - p_j(t))] \mathrm{sign}_\varepsilon(\widehat{\mathrm{con}}_i(t)) \\ &= -\sum_{i:|\widehat{\mathrm{con}}_i(t)|\geq\varepsilon} \mathrm{con}_i(t) \mathrm{sign}_\varepsilon(\widehat{\mathrm{con}}_i(t)) \end{aligned} \quad (18)$$

where $u_P(t) = [u_{P_1}(t), u_{P_2}(t), \cdots, u_{P_N}(t)]^T$.

From (14), we can derive that, for $[t_k^i, t_{k+1}^i)$, if $\widehat{\mathrm{con}}_i(t) \leq -\varepsilon$, then

$$\mathrm{con}_i(t) \leq \widehat{\mathrm{con}}_i(t) + 2|\mathcal{N}_i|(t - t_k^i) \leq \frac{\widehat{\mathrm{con}}_i(t)}{2}, \quad (19)$$

and if $\widehat{\mathrm{con}}_i(t) \geq \varepsilon$, then

$$\mathrm{con}_i(t) \geq \frac{\widehat{\mathrm{con}}_i(t)}{2}, \quad (20)$$

Inequalities (19) and (20) means that when $|\widehat{\mathrm{con}}_i(t)| \geq \varepsilon$, the signs of $\mathrm{con}_i(t)$ and $|\widehat{\mathrm{con}}_i(t)|$ are consistent, thus we have

$$\begin{aligned} \mathrm{con}_i(t)\mathrm{sign}_\varepsilon(\widehat{\mathrm{con}}_i(t)) &= \mathrm{con}_i(t)\mathrm{sign}(\mathrm{con}_i(t)) \\ &= |\mathrm{con}_i(t)| \geq \frac{|\widehat{\mathrm{con}}_i(t)|}{2} \end{aligned} \quad (21)$$

Hence, recalling (18), we have

$$\begin{aligned} \dot{V}(t) &\leq -\sum_{i:|\widehat{\mathrm{con}}_i(t)|\geq\varepsilon} \frac{|\widehat{\mathrm{con}}_i(t)|}{2} \\ &\leq -\sum_{i:|\widehat{\mathrm{con}}_i(t)|\geq\varepsilon} \frac{\varepsilon}{2}. \end{aligned} \quad (22)$$

Inequality (22) indicates that there exist a time t_s such that $|\widehat{\mathrm{con}}_i(t)| < \varepsilon$ for each DG i and all k such that $t_k^i \geq t_s$, and hence $\dot{V}(t) = 0$. Otherwise, there would exist triggers with $\dot{V}(t) \leq -\varepsilon/2$ such that $V(t) < 0$, which contradicts the positive of $V(t)$. This completes the proof.

It should be remark that, as expressed in (16), the convergence is a practical consensus result. That is the states converge to the $\varepsilon -$ neighborhood of a consensus. But, the 'disagreement' can be turned as small as desired by choosing a small enough ε. In the extreme case, if ε is chosen to be zero, the proposed control degrades to the usual average consensus control. On the other hand, (14) implies that ε also determines the number of the triggering times of the controller. The larger ε is chosen, the less the triggering times are generated. Therefore, there is a trade-off between the convergence error and the triggering times.

By using the proposed self-triggered control to achieve accurate power sharing and implementing the local frequency restoration control as (4), the two goals of the secondary control (5) and (6) can be achieved in a fully distributed manner with reduced communication and computation requirement.

IV. Verification Study

In this section, a simulation model of a MG with 4 DGs is established in MATLAB/Simulink environment to validate the proposed distributed self-triggered secondary control. In the tested MG, the DGs are modeled in detail involving the PWM control, inner current control and inner voltage control. The diagram of the test MG and its associated communication network are illustrated in Fig. 3. The parameter settings of the test MG are provided in Table. I.

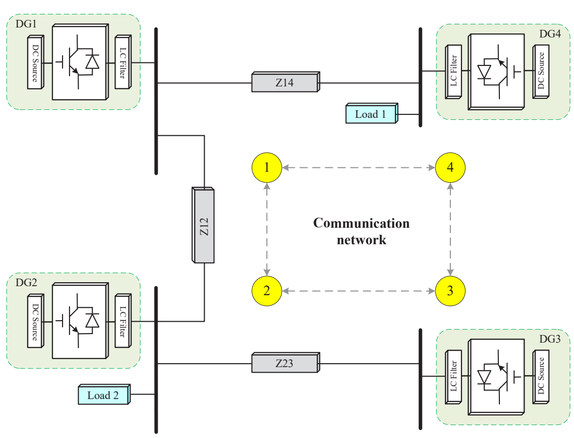

Fig. 3. The diagram of the test MG and its associated communication network.

For the control system, the time step is set to be 1 ms. The frequency reference value known for each DG is set to be 50 Hz. The desired error for each DG is chosen to be $\varepsilon = 0.005$.

The simulation process is as follow: The MG is islanded at $t = 0$ s and only regulated by the droop-based primary control; after $t = 0.5$ s, the distributed secondary control is activated; then, Load 1 decreases 5 kW suddenly at $t = 2$ s; after that, Load 1 suddenly increases 5 kW at $t = 3.5$ s. The total simulation time is 5 s.

Fig. 4 (a) and (b) show the frequencies and active power outputs of DGs, respectively. As illustrated in Fig. 4 (a), during 0 - 0.5 s, the frequencies can quickly actualize synchronization under the droop-based primary control but are deviated from

TABLE I
Parameter Settings of the Text MG

DG	**DG1**	$P_1^{\max}$	12.5 kW
		m_1	8×10^{-5}
	DG2	$P_2^{\max}$	12.5 kW
		m_2	8×10^{-5}
	DG3	$P_3^{\max}$	10 kW
		m_3	1×10^{-4}
	DG4	$P_4^{\max}$	10 kW
		m_4	1×10^{-4}
Load	**Load1**	P_1	12 kW
	Load2	P_2	15.6 kW
Z	Z_{14}	R_{14}	0.15 Ω
		X_{14}	0.58 Ω
	Z_{12}	R_{12}	0.13 Ω
		X_{12}	0.42 Ω
	Z_{23}	R_{23}	0.15 Ω
		X_{23}	0.58 Ω

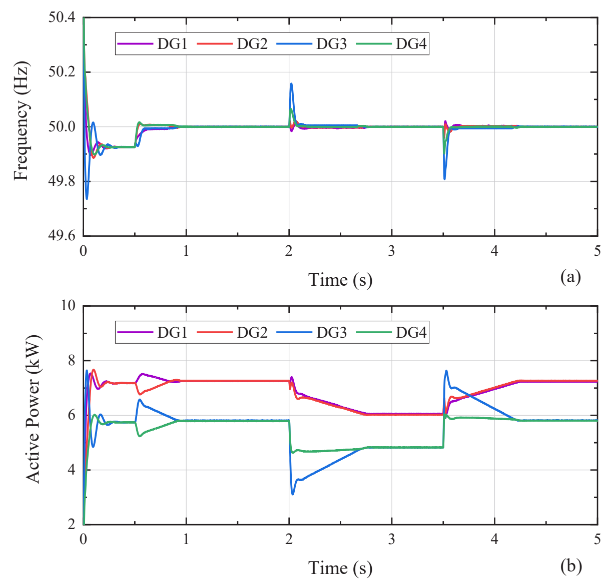

Fig. 4. The control performance of the proposed distributed self-triggered secondary control. (a) The frequencies of DGs; (b) The active power of DGs.

the nominal reference 50 Hz due to the droop mechanism. After the distributed secondary control actuating, the frequency deviations are compensated to the nominal value. Moreover, the frequencies can be restored even when step load changes occur at $t = 2$ s and $t = 3.5$ s. It can be also observed from Fig. 4 (b) that, with the distributed self-triggered power sharing controllers, DGs generate active power proportionally ($P_1 : P_2 : P_3 : P_4 = 5 : 5 : 4 : 4$) according to the same utilization profile. Furthermore, the convergence is linear since the triggers are monitored based on signum function and the designed linear clock. The performance demonstrates the effectiveness of the proposed distributed secondary control.

Fig. 5 (a) illustrates the triggering instants of each DG. Specifically, we also plot the triggering instants of each DG between 0.5 s and 2 s in Fig. 5 (b). It can be seen that each DG's controller triggers and communicates aperiodically and

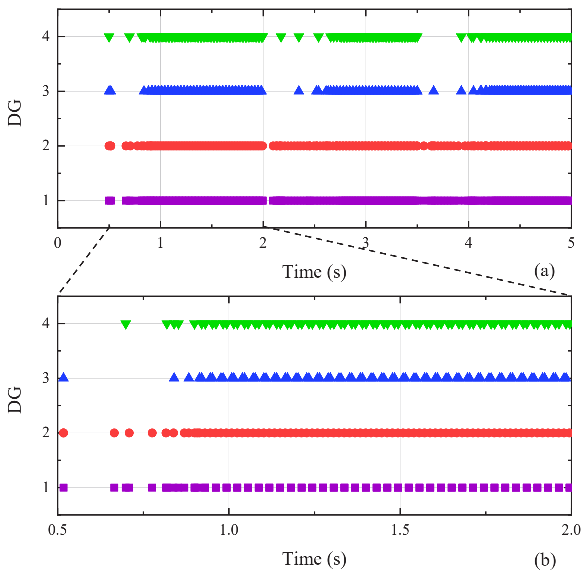

Fig. 5. The triggering instants of each DG at: (a) all the simulation time; (b) the time between 0.5 s and 2 s.

TABLE II
THE SPECIFIC TRIGGER TIMES OF EACH DG

DGs	DG1	DG2	DG4	DG5
Proposed controller	229	233	192	188
If traditional controller	4500	4500	4500	4500

intermittently, rather than continuously. Notice that our control system time step is set to be 1 ms. Thus, the total number of triggering time instants for each DG should be 4500 if the MG is equipped with traditional continuous-time-based controller. However, as Table II illustrated, the number of the triggering time instants of each DG for the self-triggered controller is only about 4.4% of the traditional one's. Therefore, with the proposed self-triggered secondary control scheme, the computation and communication requirement can be reduced significantly.

V. Conclusion

In this paper, a distributed self-triggered secondary control scheme is proposed for islanded MGs. By designing a distributed self-triggered controller for the power sharing control based on a linear clock, and coupling with a local frequency restoration control, the computation and communication burden for each DG's controller can be reduced significantly while not sacrificing the control performance. Furthermore, the design renders the controller excludes Zeno behavior naturally. The simulation results validate that the proposed distributed self-triggered secondary control can reduce more than 95 $\%$ computation and communication requirements of the controller, which is rather significant in practical applications.

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