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Need-Based Communication in Fully-Distributed Secondary Control of DC Microgrids

Pouya Shafiee
Department of Electrical Engineering
University of Kurdistan
Sanandaj, Iran
p.shafiee@eng.uok.ac.ir

Babak Abdolmaleki
Department of Electrical Engineering
University of Kurdistan
Sanandaj, Iran
abdolmaleki.p.e@gmail.com

Mojtaba Ahmadi
Department of Electrical Engineering
Razi University
Kermanshah, Iran
ahmadi1992.mojtaba@gmail.com

Qobad Shafiee
Department of Electrical Engineering
University of Kurdistan
Sanandaj, Iran
q.shafiee@uok.ac.ir

***Abstract*—Voltage regulation and current sharing are known as two main goals of DC microgrids. Distributed secondary control based on dynamic averaging consensus algorithm has been recently introduced in the literature as a viable solution. This approach, not only provides a good voltage regulation, but also guarantees load sharing will be done according to the nominal capacity of agents among the microgrids units. However, This solution is based on time-triggered communication that led to high communication burden by unnecessary data exchanging. In this paper, to prevent needless data-exchanging, the abovementioned distributed secondary controller is equipped with an event-triggered communication strategy. This need-based communication strategy reduces the communication load, considerably. The system stability analysis under the event-triggered strategy is evaluated using the Lyapunov's stability approach. The proposed strategy is applied to a DC microgrid and its performance is validated under communication disturbances and different working conditions using Simulink/ MATLAB environment.**

***Index Terms*—DC microgrids, distributed control, event-triggered control, secondary control, voltage regulation.**

I. INTRODUCTION

Microgrid (MG) is a small local network consisting of distributed generators (DGs), loads and storage systems that can act in two modes, either grid-connected or independent of the main grid [1]. MGs are categorized by DC, AC, and hybrid [2]. Although plenty of research works have focused on AC MGs in the past decade, DC MGs have drawn attention recently. In what follows, some of the DC MGs advantages comparing to the AC MGs have been listed [3]–[6]:

- More efficiency due to the existence of fewer converters,
- Simpler structure of DC-DC converters for control comparing inverters or other types of converters,
- Insignificancy of subjects like power quality, frequency control, reactive power control, harmonic currents in DC MGs,
- Most of the existing loads are DC and their connection to the DC bus is easier.

The main control objectives of DC MGs, *i.e.*, voltage regulation and proper load-sharing are reachable by primary control of the control hierarchy [7]–[9] that includes inner voltage and current loops and droop control [10], [11]. Despite easy implementation, the primary control suffers from poor voltage regulation and load-sharing due to the inherent behavior of the droop mechanism [12], [13]. Many solutions have been investigated to deal with these problems in the literature. For example, in [14] and [15] an adaptive droop control is considered to improve the performance of the system. In these research works, however, effect of line impedances is not taken into account. [12] employs a modified droop control method to improve voltage regulation and the accuracy of load-sharing which low bandwidth communication is required between DGs in the system.

The created voltage deviation by the droop controller can be eliminated by shifting the droop characteristics along the voltage axis [9]. This shift of voltage can be done by adding the correction term produced by secondary control to the droop mechanism which can improve the load-sharing operation as well [8], [16]. From the communication point of view, secondary control can be categorized as centralized [17], decentralized [18], [19] and distributed [20]–[24].

Although centralized architecture provides a basis for employment of advanced control capabilities, it is not scalable and suffers from a single point of failure [22], [25]. The decentralized architectures recently have gained more attractions. While they do not need digital communication, accurate power sharing in the presence of line impedance is still a challenge.

The so-called distributed secondary controllers employ either all-to-all [20], [22] or neighbor-to-neighbor [23], [24] communication. In the first strategy, load-sharing is not performed based on the nominal capacity of DGs. In order to avoid this problem and creating a certain level of awareness between units, the neighbor-to-neighbor data-exchanging can be used which composes a fully-distributed structure. Such a structure is often implemented based on consensus algorithm [26]. The consensus is a type of control protocol which allows agents (*e.g.,* DGs) to reach an agreement by exchanging their information only with their neighbors. This protocol is categorized as "leader-follower" [27] and "leaderless" [28] where the former is used to leader tracking and the latter for convergence to a common value. In a fully-distributed secondary control, need for complex communicating network and single-point of failure have been resolved. Besides, not only good voltage regulation but also accurate load-sharing is achieved according to the nominal capacity of agents [7].

Sampled-data exchanging in a fully-distributed structure, is commonly done by constant frequencies. This type of data-exchanging is known as "Time-Triggered" communication [29].

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This so-called periodic communication may lead to over usage of the bandwidth by receiving and sending unnecessary data, specifically, in large scale systems [30], [31].

As an alternative, the aperiodic data-exchanging can be used to prevent the time-triggered communication problems. This type of communication is called "Event-Triggered" data-exchanging [32]. The event-based communication is an efficient strategy in which the control signal updating and data-exchanging is done only when the states of agents go beyond a pre-defined threshold. Recently, event-based communication strategy has been used in the power systems applications [33]–[35].

In [33], an event-triggered based communication is employed for wide-area damping control in which event condition is achieved from a stability criterion. In this paper, stability of the closed-loop system is guaranteed via the input-to-state stability (ISS) technique, however, the whole data of network needs to be known by each DG to ensure the stable performance. An adaptive event-based distributed secondary control is introduced in [34] for proper voltage regulation and load sharing of the DC MGs. Although it uses parameters projection law based on state estimate for communication burden reduction, access to the global GPS signal is required. Reference [35] presents an event-based dynamic averaging consensus algorithm (DACA) for achieving global voltage regulation and proper load-sharing in the DC MGs. In [35], convergence and stability of the proposed scheme using the Lyapunov stability criterion have been discussed, however, communication models and Zeno behavior have not been taken into account.

This paper proposes an event-triggered distributed control with a new event condition for the DC MGs. The proposed event-condition verifies Zeno behavior by considering a constant term. This strategy considerably reduces the amount of exchanged data between the DGs in the system.

The rest of this paper is organized as follows. Section II provides system modeling including physical, control and communication layers. Section III presents the event-triggered strategy. Effectiveness of the proposed event-based approach is verified using numerical simulations in Section IV and Section V concludes the paper.

II. System Modeling

Fig. 1 shows the hierarchical control structure for stand-alone MGs. This structure includes three communication, physical and control layers. The following subsections describe the above-mentioned layers.

a) Communication Layer: The communication network of a multi-agents MG can be modeled as a graph that each DG is regarded as a node and the edges of this graph show the communication links. Communicating network in the form of a graph is commonly denoted as $G_r = (V_G, E_G, A_G)$ with a non-zero limited set from N nodes as $V_G = (v_1, v_2, \cdots, v_N)$, a set of edges as $E \subset V_G \times V_G$ as well as, adjacent matrix $A_G = [a_{ij}] \in R^N \times R^N$. In adjacent matrix, a_{ij} shows weight of the exchanged information between i and j agents, *e.g.*, DGs. If the i and j agents are connected by an edge $(v_i, v_j) \subset E$, then $a_{ij} \succ 0$, otherwise $a_{ij} = 0$. The neighbors of node i is shown by N_i. If $j \in N_i$, then v_i can receive the information from v_j. By considering bidirectional communication links, that is, if for each i and j the expression of $(v_i, v_j) \in E \Leftrightarrow (v_j, v_i) \in E$ is met, then the proposed graph is called "undirected", otherwise the graph is "directed graph".

The Laplacian matrix is stated as $L = D - A$ where its eigenvalues describe the general dynamics of the system. D is a diagonal matrix which is said "in-degree, out-degree" matrix and is stated as $D = diag\{d_i\}$ where $d_i = \sum_{j \in N_i} a_{ij}$. "In-degree, out-degree" matrix is a matrix in which the number of entered edges to its vertices, exactly be equal to the number of exited edges from the same vertices [36].

b) Physical and Control Layers: The physical and control layers of a DG in a droop-based MG are shown in Fig. 2 where each DG includes a DC-DC converter, primary controller (voltage, current and droop controllers) and a DACA based fully-distributed secondary control. The DC-DC converter is equipped with a filter and connected to the rest of the DGs in the system via line impedance. Since the DC-DC converter with voltage and current primary controllers have high bandwidth, their dynamics can be ignored and modeled as a first-order filter along with controllable voltage source which is controlled by droop mechanism. In other words, each DG can be considered as a droop-controlled voltage source. Therefore, the DACA can be written in the following form:

$$\dot{\bar{x}}_i(t) = \dot{x}_i(t) + u_i(t) \tag{1}$$

where $\bar{x}_i \in \left[\bar{v}_i, \bar{i}_{i(pu)}\right]$, $x_i \in \left[v_i, i_{i(pu)}\right]$ and $u_i \in [u_{\bar{v}_i}, u_{\bar{i}_{i(pu)}}]$ are the averaged states, the measured states and the input vector of i^{th} DG, respectively. Thus, one can write:

$$\dot{\bar{v}}_i(t) = \dot{v}_i(t) - \sum\nolimits_{j \in N_i} c_v \left(\bar{v}_i(t) - \bar{v}_j(t)\right) \tag{2}$$

$$\dot{\bar{i}}_{i(pu)}(t) = \dot{i}_{i(pu)}(t) - \sum\nolimits_{j \in N_i} c_{\bar{i}} \left(\bar{i}_{i(pu)}(t) - \bar{i}_{j(pu)}(t)\right) \tag{3}$$

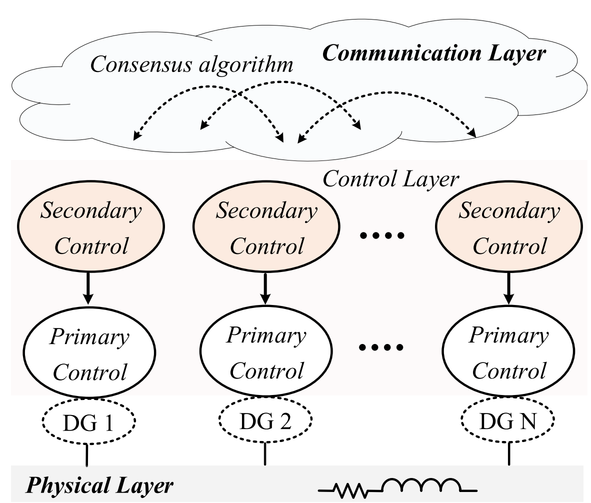

Fig. 1. A MG equipped with physical, control and communication layers

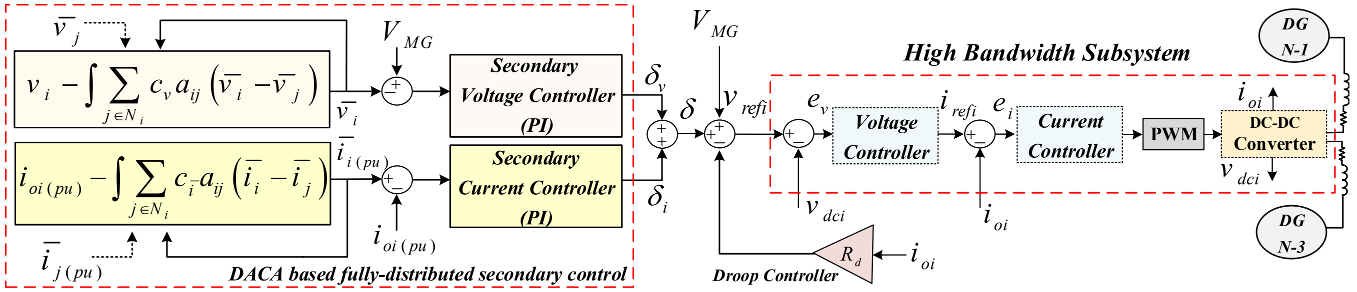

Fig. 2. Physical and control Layers of a DG in a typical droop-based MG. The control layer composed of primary and distributed secondary control.

where c_v and $c_{\bar{i}}$ are the coupling gains of voltage and current in DACA, respectively. Using these gains, the convergence speed and the performance of the system can be tuned. Notice that the per-unit of current, *i.e.*, $i_{i(pu)}$ is equal to the output current of i^{th} DG divided by its maximum allowed current, *i.e.*, $i_{i(pu)} = i_i/i_{i(\max)}$. According to (2) and (3), the DACA of each node collects information from its neighbors and multiples them by a_{ij} for updating the stored variables. One can see from Fig. 2 that the created correction term produced by the DACA *i.e.*, $\delta = \delta_v + \delta_i$ is added to the droop mechanism to compensate the drop of voltage induced by droop controller and improves the load sharing.

$$V_{ref} = V_{MG} - R_d i_o + \delta_v + \delta_i \tag{4}$$

where δ_v and δ_i are the produced voltage correction terms by the DACA of voltage and current, respectively. As well as, V_{ref}, V_{MG} and R_d are the produced reference voltage by droop controller, the nominal voltage of MG and the resistance of droop mechanism, respectively. According to (2), the objectives of DACA for voltage and current is convergence the averaged voltages to the MG's reference voltage and convergence the current per-unit of each DG to the averaged currents per-unit of DGs. So, using DACA, Despite good voltage regulation, the proper load-sharing is achieved according to the nominal capacity of units.

III. Event-based Fully-Distributed Secondary Control

As mentioned already, the DACA in time-triggered implementation can lead to unnecessary communication, specifically in the steady-state mode which makes over usage of the communication bandwidth. Therefore, introducing a need-based data-exchanging strategy to prevent this problem can be effective. Hence, in this section, for reducing the communication burden, the DACA is equipped with an event-based communication strategy. This strategy reduces the amount of communication in both transient and steady-state modes. It ensures that the time intervals between consecutive communication are positive (*i.e.*, nonoccurrence of Zeno phenomenon [37]).

In the event-triggered implementation, the control signal re-computing and data exchanging is done according to violating an event condition. Generally, the event-based control systems have two mechanisms that are control signal computing and control signal updating time. The control input in the time-triggered implementation based DACA can be expressed as,

$$u_i(t) = -\sum\nolimits_{j\in N_i} a_{ij}\left(\bar{x}_i(t) - \bar{x}_j(t)\right) \tag{5}$$

where $\bar{x}_i$ and $\bar{x}_j$ are the averaged state variables that i^{th} agent sends to its neighbors and receives from them, respectively. In an event-based control scheme, the control signal $u_i(t)$ is computed according to the last event information. This control input must remain constant to the next event time, *i.e.*,

$$u_i(t) = u_i\left(t_k, t_{k'}\right) = -\sum\nolimits_{j\in N_i} a_{ij}\left(\hat{x}_i(t_k) - \hat{x}_j(t_{k'})\right) \tag{6}$$

in which t_k and $t_{k'}$ are the last event times of i^{th} DG and its neighbors. Also, $\hat{x}_j$ and $\hat{x}_i$ are the latest received data from neighbors and the last sent data to the neighbors by i^{th} agent, respectively. One can write (6) as $u(t) = -L\hat{x}(t_k, t_{k'})$ where L is the laplacian matrix of the communication network. By considering the derivative of the state variables of the i^{th} DG in (1) as disturbance, *i.e.*, $w_i(t) = \dot{x}_i(t)$, the final form of DACA can be expressed based on global variables as follows:

$$\dot{\bar{x}} = w - L\hat{x}. \tag{7}$$

Moreover, the error signal of the i^{th} DG is expressed as the difference of the latest sampled-data and the averaged data at each time, *i.e.*,

$$e_i(t) = \hat{x}_i(t_k, t_{k'}) - \bar{x}_i(t) \tag{8}$$

Notice that the event-based system designing includes a good choice of the event condition to ensure the DACA converging. Toward this end, it is assumed that the absolute value of the defined error has the following threshold:

$$|e_i(t)| \leq \sigma_i|\hat{z}_i(t_k, t_{k'})| + \gamma_i \tag{9}$$

where σ_i, γ_i and $|.|$ are the speed control term of Lyapunov's derivative reduction, non-zero positive constant to assure the Zeno phenomenon and absolute value of functions, respectively. By violating this threshold, an event is triggered and accordingly the control signal is updated. It is to be noted that by considering γ_i in (9), the error term always has a small place for growing and the event condition is no longer triggered by any small error. This guarantees that the Zeno behavior is not occurred. The triggering mechanism has been shown in

Fig. 3. When the error goes ahead from the defined threshold, an event is triggered and new sampling and sending of data to the related agents is allowed. Let us consider a Lyapunov's energy function as $V = (\bar{x}^T L\bar{x})/2$. By differentiating of this function and using (7), one can write,

$$\dot{V} = \bar{x}^T Lw - \bar{x}^T LL\hat{x}. \tag{10}$$

In this paper, it is assumed that the continuous access to the neighbors data is not existed and only the awareness from the latest updating of DGs is possible. Therefore, using (8), (10) can be stated as,

$$\dot{V} = -\hat{x}^T LL\hat{x} + \hat{x}^T Lw - e^T Lw + e^T LL\hat{x} \tag{11}$$

Consider,

$$\hat{z}_i(t_k, t_{k'}) = \sum_{j\in N_i} a_{ij} \left(\hat{x}_i(t_k) - \hat{x}_j(t_{k'})\right) \tag{12}$$

which also can be stated as $\hat{z} = L\hat{x}$. In regard to this note and available symmetry in communication network $\left(i.e., L = L^T\right)$, (11) can be modified as,

$$\dot{V} = -\hat{z}^T \hat{z} + \hat{z}^T w - (Le)^T w + (Le)^T \hat{z}. \tag{13}$$

The recent relation has been stated according to the global variables whereas for event condition designing, (13) should be written as the local variables. Therefore,

$$\begin{aligned}\dot{V} = &-\sum_i \hat{z}_i^2(t_k, t_{k'}) + \sum_i w_i(t)\hat{z}_i(t_k, t_{k'}) \\ &+\sum_i \sum_{j\in N_i} w_i(t)\left(-e_i(t)\right) + \sum_i \sum_{j\in N_i} e_j(t)w_i(t) \\ &+\sum_i \sum_{j\in N_i} \hat{z}_i(t_k, t_{k'})e_i(t) + \sum_i \sum_{j\in N_i} \hat{z}_i(t_k, t_{k'})\left(-e_j(t)\right)\end{aligned} \tag{14}$$

Henceforth, for simplicity in showing relations, the arguments of functions is not written. Considering $\sum_i \sum_{j\in N} m_i n_i = \sum_i |N_i| m_i n_i$, (14) can be written as,

$$\begin{aligned}\dot{V} \le &-\sum_i |\hat{z}_i|^2 + \sum_i |N_i| |\hat{z}_i| |e_i| + \sum_i |w_i| |\hat{z}_i| \\ &+\sum_i \sum_{j\in N_i} |\hat{z}_i| |e_j| + \sum_i |N_i| |w_i| |e_i| + \sum_i \sum_{j\in N_i} |w_i| |e_j|.\end{aligned} \tag{15}$$

Using (9), One can write,

$$\begin{aligned}\dot{V} \le &-\sum_i |\hat{z}_i|^2 + \sum_i |w_i| |\hat{z}_i| \\ &+\sum_i |N_i| |\hat{z}_i| \left(\sigma_i|\hat{z}_i| + \gamma_i\right) + \sum_i \sum_{j\in N_i} |\hat{z}_i| \left(\sigma_j|\hat{z}_j| + \gamma_j\right) \\ &+\sum_i |N_i| |w_i| \left(\sigma_i|\hat{z}_i| + \gamma_i\right) + \sum_i \sum_{j\in N_i} |w_i| \left(\sigma_j|\hat{z}_j| + \gamma_j\right)\end{aligned} \tag{16}$$

Using the Young's inequality as $|x| |y| \le (a/2) x^2 + (1/2a) y^2 \quad \forall a > 0$, (16)can be stated as,

$$\begin{aligned}\dot{V} \le \;&-\sum_i (1 - \sigma_i |N_i|) |\hat{z}_i|^2 + \sum_i (1 + \sigma_i |N_i|) |w_i| |\hat{z}_i| \\ &+\sum_i \sum_{j\in N_i} \sigma_j (a/2) |\hat{z}_i|^2 + \sum_i \sum_{j\in N_i} \sigma_j (1/2a) |\hat{z}_j|^2 \\ &+\sum_i \gamma_i |N_i| |\hat{z}_i| + \sum_i \gamma_i |N_i| |w_i| + \sum_i \sum_{j\in N_i} \gamma_j |\hat{z}_i| \\ &+\sum_i \sum_{j\in N_i} \sigma_j |\hat{z}_j| |w_i| + \sum_i \sum_{j\in N_i} \gamma_j |w_i|\end{aligned} \tag{17}$$

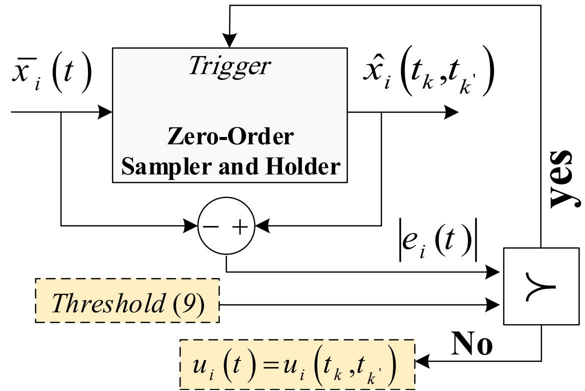

Fig. 3. Event-triggered mechanism

Since the communication network has been considered symmetric, the indices of $\sum_i \sum_{j\in N_i} \sigma_j (1/2a) |\hat{z}_j|^2$ can be interchanged. Therefore (17) can be modified as,

$$\begin{aligned}\dot{V} \le \;&-\sum_i \left(1 - \sigma_i |N_i| - \sigma_i |N_i| \left(\tfrac{a^2+1}{2a}\right)\right) |\hat{z}_i|^2 \\ &+\sum_i \left(|w_i| + 2\sigma_i |N_i| |w_i| + \gamma_i |N_i| + \sum_{j\in N_i} \gamma_i\right) |\hat{z}_i| \\ &+\sum_i \left(\sum_{j\in N_i} \gamma_i + \gamma_i |N_i|\right) |w_i|\end{aligned} \tag{18}$$

One can see that in (18), if the coefficient of $|\hat{z}_i|^2$ is positive, the first term is negative. That is,

$$1 - \sigma_i |N_i| - \sigma_i |N_i| \left(\frac{a^2+1}{2a}\right) > 0 \tag{19}$$

which result in $\sigma_i < \left(2a \big/ (a+1)^2 |N_i|\right)$. Therefore, by reasonable choosing of γ_i and $\sigma_i \in \left(0, 2a \big/ (a+1)^2 |N_i|\right)$, the derivative of Lyapunov's function is negative definite and this function has a decreasing procedure. Toward this end, the considered threshold for error in (9), results in asymptotic convergence of the system under the event-triggered strategy. Therefore, it can be included that (9) is a valid event triggering condition for i^{th} DG.

It should be emphasized that by very small choosing of σ_i and γ_i the event condition is triggered via any small error. For MG applications, due to high frequency switching noise of converters in current and voltage signals, the event condition may be triggered incorrectly. On the other hand, by choosing large amounts of σ_i and γ_i the event condition will be large numerically and this may be led to the event condition can not be triggered for small perturbations. Thus, a trade-off between sensitivity and noise rejection must be considered.

IV. Simulation Results

In this paper, to verify effectiveness of the proposed controller, a 48V DC MG consisting of five DG is simulated in MATLAB/SimPowerSystem software environment. Fig. 4 shows the physical and cyber layers of the system. As well as, The characteristics of droop coefficients and local loads of units are listed in Table I.

In the proposed structure, each DG has a local load while all of units are responsible for feeding a global load. The communication network is shown in Fig. 4, while its parameters are listed below. For $i \in [1,5]$, $\gamma_i = 0.001$ and $\sigma_i = 0.15$ have been selected. Performance of the proposed event-based controller is studied under link failure and plug-and-play (PnP) capability scenarios.

Fig. 5(a)-(b) show the system's performance under global load changing and communication link failure. Before $t =$ 2s, the MG is operated with droop control where voltages deviation from the nominal value is observed. After activation of the proposed event-based secondary controller at $t =$ 2s, the deviation of voltages is compensated and the currents are shared properly according to the nominal capacity of DGs. At $t =$ 4s, the global load is changed from 72Ω to 36Ω. It can be seen that the voltages, after a small drop, are restored to the nominal voltage and the units have increased their currents to support the required current for the new global load. From $t =$ 6s to $t =$ 9s, the communication link between DG2 and DG4 is failed and at $t =$ 7.5s, the global load is decreased to 72Ω. One can see from Fig. 5(b), even when the communication network failing, the load-sharing is not affected and load has been shared properly.

Fig. 5(c)-(d), indicate the event instants for the proposed voltage and current controllers. As can be observed from this figure, most of data-exchanging occur within the transient modes (*i.e.,* load changes), Thus, many redundant communications are avoided through the proposed need-based communication strategy. Moreover, it is obvious that the time interval between consecutive event times is positive, *i.e.,* the Zeno phenomenon has not occurred.

Fig. 6(a)-(b), indicate the PnP scenario under the proposed scheme. In this scenario, all requirements (Laplacian matrix and communication network) are the same as the prior scenario. Here, 4^{rd} is plugged-out from the system at $t =$ 4s and plugged-in again at $t =$ 8s. During this time interval, the separated DG only feeds its local load as well as loses all the communication links with its neighbors, that is, DG4 will be isolated from the communication point of view. For system's performance evaluating under PnP, a change in global load from 72Ω to 36Ω is considered. By disconnecting DG4, other DGs increase their participation in load-sharing according to their nominal capacity. Fig. 6(c)-(d), show the event instants for this scenario. Therefore, it can be observed that many unnecessary data-exchanging have been avoided through the proposed strategy in this scenario.

V. Conclusion

This paper proposes an event-triggered based fully-distributed secondary control for proper voltage regulation and current sharing of dc microgrids. To prevent unnecessary data-exchanging between units, the proposed consensus-based controller is equipped by a need-based strategy that guarantees the system stability and Zeno-freeness phenomena. Effectiveness of the proposed need-based secondary control is validated by simulation of a test MG under load changing, PnP and link failure case studies.

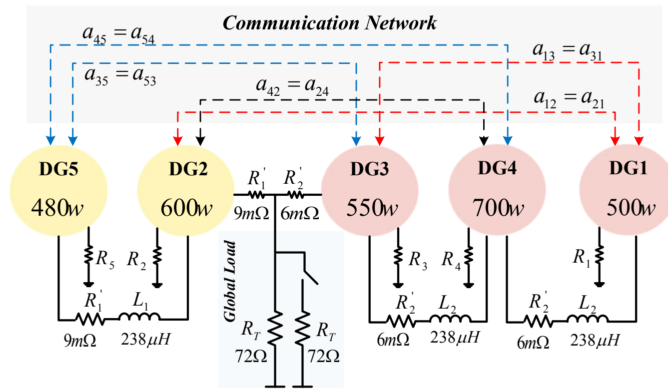

Fig. 4. The test MG with communication network

TABLE I
CHARACTERISTICS OF UNITS

		Droop Coefficient (mΩ)	Local Load (Ω)
# DG	1	184	23.04
	2	153	19.02
	3	167	25.6
	4	131	28.8
	5	192	19.2

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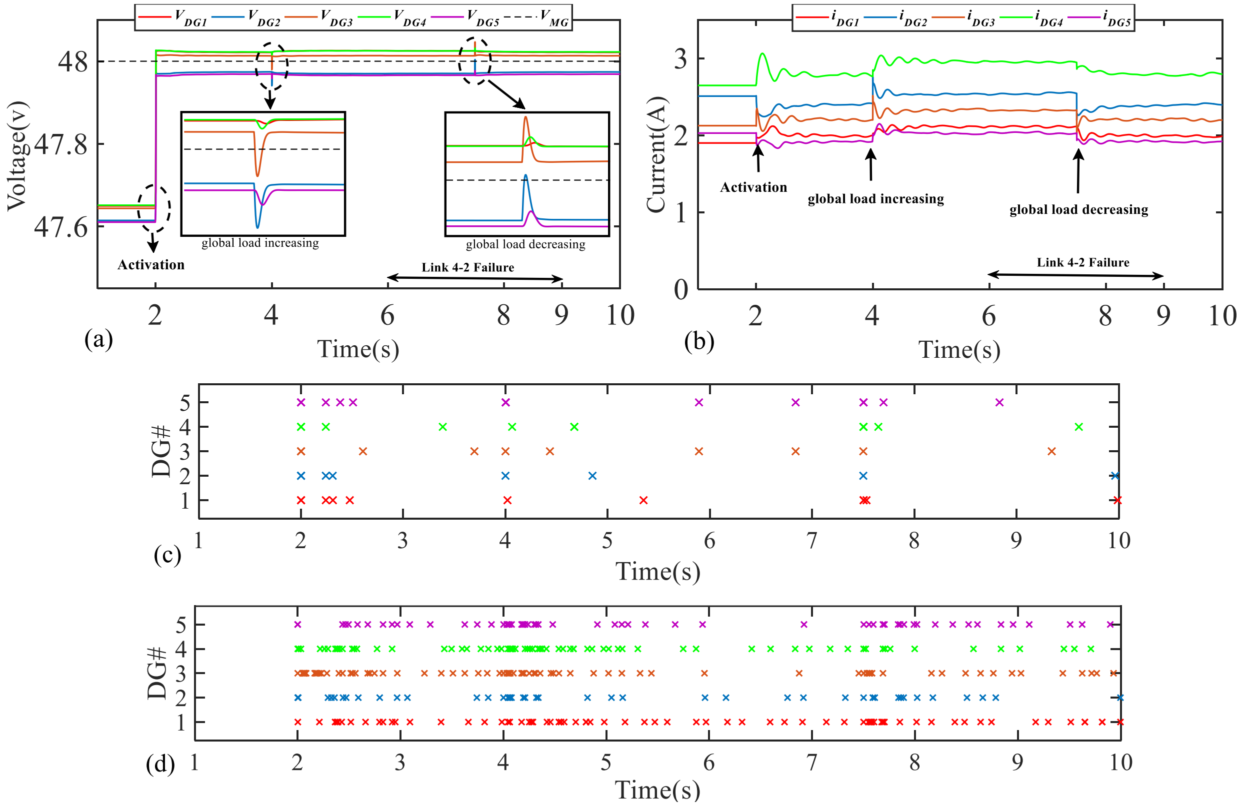

Fig. 5. Performance of the proposed controller under load changing, and link failure: (a) voltages, (b) currents, (c) and (d) communication instants of voltage and current

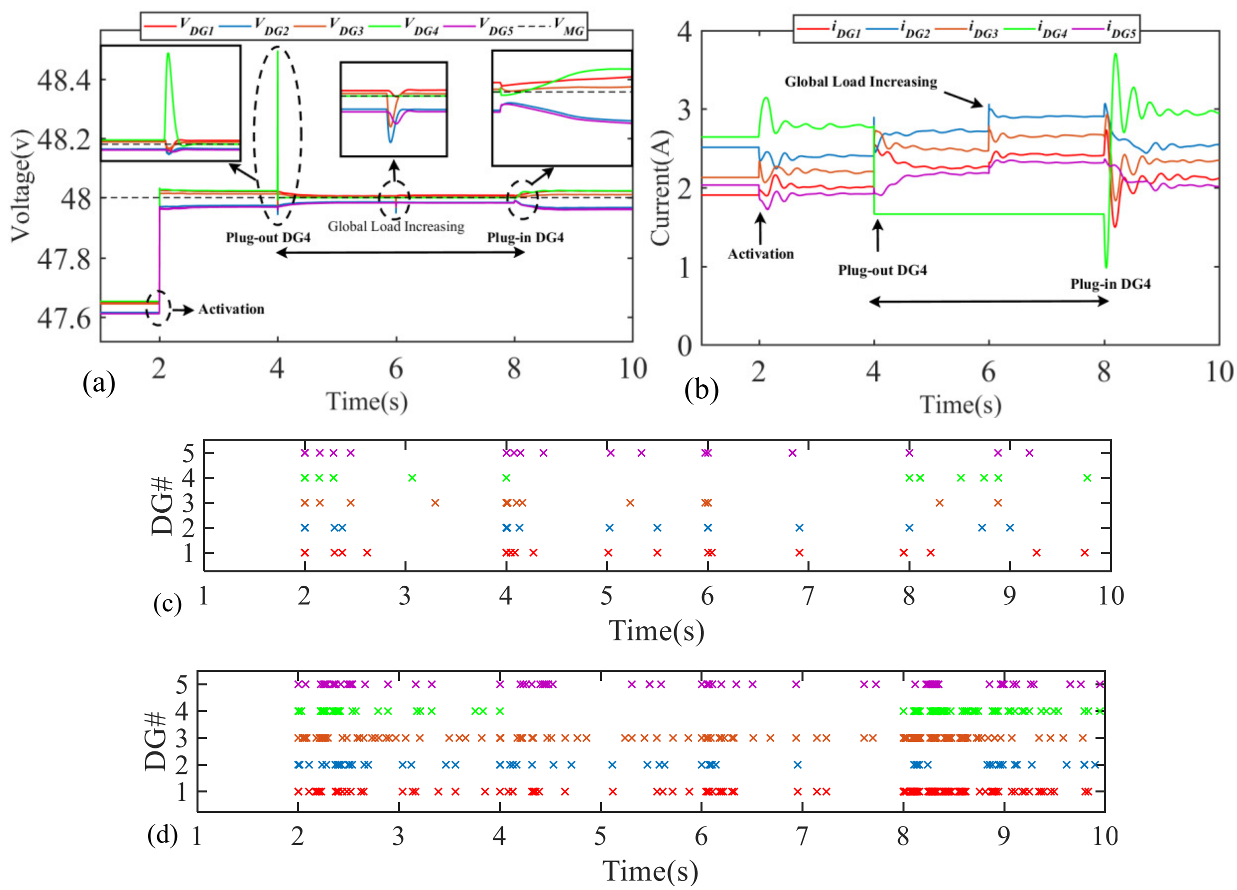

Fig. 6. Performance of the proposed controller under load changing, and PnP: (a) voltages, (b) currents, (c) and (d) communication instants of voltage and current.

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