Distributed Event-Triggered Consensus-Based Control for Current Sharing and Voltage Stabilization of DC Microgrids

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Abstract: In this paper, the problem of distributed event-based control of large scale power systems is addressed. Towards this end, a Direct Current (DC) microgrid that is composed of multiple interconnected Distributed Generation Units (DGUs) is considered. Voltage stability is guaranteed by utilizing decentralized local controllers for each DGU. A distributed discrete-time event-triggered (ET) consensus-based control strategy is then designed for current sharing in the DGUs. In this mechanism, the transmissions occur while a specified event is triggered to prevent unessential utilization of communication resources. The asymptotic stability of the ET-based controller is shown formally by using Lyapunov stability via linear matrix inequality (LMI) conditions. The effectiveness of the proposed methodology is demonstrated and substantiated in simulation case study.

Keywords: Distributed event-based control; DC microgrid; Current sharing; Asymptotic stability; Consensus control; Linear matrix inequality (LMI).

1. INTRODUCTION

A microgrid (μG) is a localized low-voltage electrical distribution network that consist of clusters of Distribution Generation Units (DGUs), loads, and storage systems interconnected via power lines (Lasseter and Piagi, 2004). The standard model of microgrid that is utilized for commercial, residential and industrial consumers is the AC power generation microgrid that has attracted several fields of studies focused on control of AC mGs (Schiffer et al., 2015; Simpson-Porco et al., 2016). However, a number of advantages of DC energy systems such as efficient converters availability, appropriate interfacing of batteries and DC energy sources, minimal power losses, and ever-growing number of DC loads have made them more interesting research topics (Dragičević et al., 2015; Justo et al., 2013). Being deployed in aircraft, trains, modern-designed ships and large charging facilities for electric vehicles are some of the typical examples of DC microgrid utilization. For all these reasons, DC microgrids are attracting growing interest and have recently received much research attention (Cucuzzella et al., 2018a).

Current sharing and voltage regulation of DC microgrids are the main two control challenges of these systems. The optimal voltage regulation strategy results in the desired output voltage of each microgrid, while the current-sharing control strategy divides, shares, and dedicates equal cur-

rent to each DC microgrid (Trip et al., 2018; Cucuzzella et al., 2018b,a; Tucci et al., 2016). Hierarchical control schemes have been developed in the literature to achieve both objectives (Guerrero et al., 2010). Although centralized controllers satisfy the voltage stabilization and precise current sharing goals (Guerrero et al., 2010), the computational and communication burden of these architectures increase by the larger size of microgrids. Moreover, a single-point-of-failure in the central control unit may lead to malfunction of the entire system (Meng et al., 2015). This is the main reason why decentralized and distributed regulators, such as droop controllers (Guerrero et al., 2010), are preferred. Being a communication-less approach, droop controllers may lead to voltage deviations from reference values. In this way, a secondary control layer with consensus algorithms is deployed and combined with the droop controller to deal with the deviation problem (Zhao and Dörfler, 2015; Meng et al., 2015).

Scalability criteria have become one of the most important characteristics of control-scheme designs in distributed systems. Physical wide range of distributed microgrid systems has attracted researches' interest toward scalable control strategies, particularly aiming at current (power) sharing (Zhao and Dörfler, 2015; De Persis et al., 2018; Prabhakaran et al., 2017; Cucuzzella et al., 2018a; Trip et al., 2018). In distributed control, each subsystem can receive information from its neighbors which could result in the performance improvement. Thus, it has emerged as a practical scheme for large-scale systems as in Chen et al. (2016); Conte et al. (2016). On the other hand,

information exchanges among subsystems are transmitted over networks which may cause heavy communication burden. In order to avoid the unnecessary utilization of communication resources, much attention has been paid to event-triggered control (ETC) techniques in recent years, see for instance (Peng et al., 2017; Batmani et al., 2017; Wu et al., 2017; Gu et al., 2017; Davoodi et al., 2017).

In distributed ETC for large-scale systems, each subsystem transmits its information through the network based on certain event-triggering conditions. Data transmission only takes place when event-triggering conditions are violated, and hence the communication cost is considerably decreased (Shi et al., 2018).

In (Pullaguram et al., 2018), the DC microgrid is controlled with an ET communication-based voltage droop control strategy to ensure power sharing. The convergence of the consensus is shown by Lyapunov stability theory. The proposed DC microgrid is composed of distributed energy resources (DERs) in which the DER layer is composed of a distributed source connected to a DC/DC converter with a specific duty cycle.

A distributed nonlinear ETC approach is developed in (Han et al., 2017) for current sharing and voltage regulation in an electrical network model for a DC microgrid. This DC microgrid includes converters, and local and public loads. The controller is designed based on Lyapunov stability criteria to guarantee the convergence and global stability.

The above-mentioned ET-based control approaches for a DC microgrid do not exhibit the Zeno behavior (infinite events over a finite time interval) exclusion which is an important item in evaluation of the controller performance. Indeed, the Zeno phenomenon describes the behaviors in the ET-based controller that the system is subjected to an unbounded number of events in a finite and bounded length of a given time interval. This can happen when the controller unsuccessfully attempts to satisfy the event-triggered condition faster and faster which leads to sending infinite number of data in a finite interval. In other words, the feasibility and practicality of the ET-based controller is concluded by showing the Zeno behavior exclusion in the system and this important fact is not guaranteed in the above approaches .

In this paper, a model of DC microgrid is considered as the combination of different types of DGUs, and the state space model of the microgrid is considered for the controller design. In this model, voltage stabilization is guaranteed using a decentralized local controller for each DGU. A distributed discrete-time ET consensus-based controller is then designed for current sharing in DGUs. A state-dependant threshold is designed for proper ET condition using the secondary controller. Finally, stability of the overall microgrid is guaranteed by using the Lyapunov stability results and the design parameters are found via solving an LMI. The advantages of the proposed approach are reducing the cost of the network communication and improving its security since the data transmission is based on the ETC system conditions.

The main contribution of this paper is the study of a discrete-time ET consensus-based control methodology of
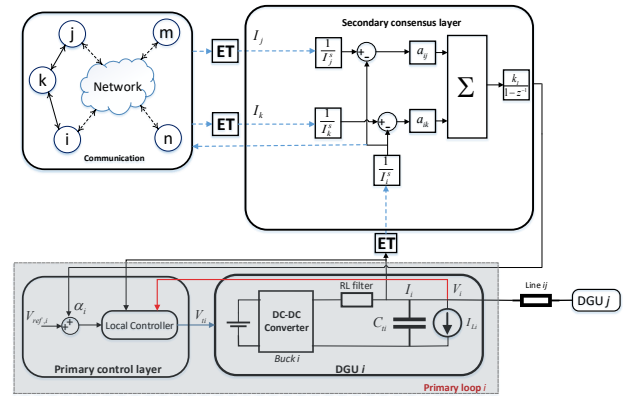

Fig. 1. The i-th DGU having a complete hierarchical control in communication with its neighbors.

the DGU which guarantees the current sharing and at the same due to the discrete-time event-triggered framework, it is guaranteed that the Zeno phenomenon is excluded.

The remainder of the paper is organized as follows. In Section 2, the system description is elaborated. The problem formulation is presented in Section 3. The stability analysis of the overall microgrid and the main results are analyzed in Section 4. In Section 5, simulation results are presented to demonstrate the validity of the proposed approach and to demonstrate the efficiency of the proposed ET consensus-based method in achieving voltage regulation and current sharing of the DC microgrid. Finally, conclusions are provided in Section 6.

2. SYSTEM DESCRIPTION

The MG ystem model and control schemes are described in this section. A DC microgrid is composed of N interconnected DGUs through power lines. The microgrid is represented by a directed graph (digraph) $\mathcal{G}_e = (\nu, \varepsilon_e, w_e)$ where the nodes, $\nu \in \{1, ..., N\}$, represent the DGUs, the edges, $\varepsilon_e \in \nu \times \nu$, represent the power lines, and the diagonal matrix w_e with $w_{e,ii} = w_{e,i}$ represents the weight matrix, where $w_{e,i}$ is the weight associated with the edge $e_i \in \varepsilon_i$. Note that direction of edges specifies a reference direction for positive currents, and the edges weights are related to the corresponding line conductances, $\frac{1}{R_{ij}}$. The Laplacian matrix of the physical system is given by $L_e = q_e w_e q_e^\top$, where q_e is the incidence matrix of $\mathcal{G}_e$. The set of neighbors of the ith node is denoted by $N_i = \{j \in \nu : (i, j) \in \varepsilon_e\}$.

A hierarchical control architecture with two objectives of maintaining local stability of subsystems and achieving consensus of the second state variable among subsystems of the large-scale system is considered. The DGU with ET hierarchical control is depicted in Fig. 1. The renewable resource in each DGU is modeled as a DC voltage source that supplies a local load through a Buck converter. The local DC load is connected to the PCC through an RL filter.

The dynamics of the i-th DGU is governed by the following representation:

$$\frac{dV_i(t)}{dt} = \frac{1}{C_{ti}}(I_i(t) - I_{Li}(t)) + \sum_{j \in N_i} \frac{1}{C_{ti}R_{ij}}(V_j(t) - V_i(t)),$$

$$\frac{dI_i(t)}{dt} = \frac{1}{L_{ti}}V_{ti}(t) - \frac{R_{ti}}{L_{ti}}I_i(t) - \frac{1}{L_{ti}}V_i(t), \ i = 1, ..., N, \tag{1}$$

where $V_i(t)$, $I_i(t)$, $C_{ti}(t)$, $L_{ti}(t)$, R_{ti}, R_{ij}, and $I_{Li}(t)$ denote load voltage, generated current, shunt capacitor, filter inductance, resistance, line resistance, and current demand, respectively. $(V_i(t), I_i(t))$ denote the states, $V_{ti}(t), I_{Li}(t)$ denote inputs, $V_j(t)$ is the Point of Common Coupling (PCC) voltage of the DGUi's neighbors, and $\frac{1}{R_{ij}}$ is the conductance of the power line connecting DGUs i and j. Current demand $I_{Li}(t)$ is assumed as a disturbance.

The primary decentralized controller is designed to regulate the voltage at each PCC while guaranteeing stability of the overall microgrid. Measurements of $V_i(t)$ and $I_i(t)$ are used with the local regulator of each DGU to generate the command $V_{ti}(t)$ of the i-th Buck converter and ensures it tracks a reference signal $V_{ref,i}(t)$.

Generally, some DGUs may not able to supply local loads and need power from other DGUs. Therefore, the secondary controller is designed to share the currents between DGUs proportionally to their generation capacity. Although the current sharing holds, the voltages at PCCs may have deviations from their nominal values. Hence, another objective of the secondary controller is to ensure the same average voltage value among all PCCs.

In other words, in order to improve the efficiency of generation, it is generally desired that the total current demand is shared among different DGUs in proportion to the capacity of their corresponding energy sources (proportional current sharing). Conventionally, each DGU broadcasts its current at every time instant which may lead to inefficient utilization of communication resources. Instead of this conventional approach, an ET-based mechanism is introduced in this paper, in which the transmission occurs only when a certain event is triggered.

3. PROBLEM FORMULATION

3.1 DC Microgrid Model

The dynamics of the i-th DGU in the state space representation can be written as follows:

$$\dot{x}_i(t) = A_{ii}x_i(t) + \sum_{j \in N_i} A_{ij}x_j + B_i u_i(t)$$
$$+ M_i d_i(t), \tag{2}$$
$$y_i(t) = C_i x_i(t),$$
$$z_i(t) = H_i x_i(t), \qquad i = 1, 2, ..., N,$$

where $x_i(t) = [V_i(t), I_i(t)]^\top$ denotes the local state, $u_i(t) = V_{ti}(t)$ denotes the primary control input, $d_i(t) = I_{Li}(t)$ denotes the exogenous input, $y_i(t)$ denotes the measurable output, and $z_i(t) = V_i(t)$ denotes the controlled output of each subsystem. It is assumed that both state variables are measurable, i.e. $y_i(t) = x_i(t)$. The matrix A_{ii} is the local state transition matrix, A_{ij} describes the interconnection between subsystems i and j, B_i is the primary matrix, and C_i is the local output transition matrix. These matrices are defined in (Tucci et al., 2015a).

3.2 Hierarchical Control Model

The hierarchical control strategy which guarantees the local stability of subsystems and achieves current sharing among DGUs is now considered. This two-layer control strategy is described in the following.

Decentralized primary controller: In the first step, an augmented state variable $\zeta_i(t)$ is defined to provide the required integrator action via the primary controller. The dynamics of $\zeta_i(t)$ is given by $\dot{\zeta}_i(t) = V_{ref,i}(t) - V_i(t) + \alpha_i(t)$, where $V_{ref,i}(t)$ denotes the reference for voltage $V_i(t)$, and $\alpha_i(t) \in \mathbb{R}^{n_{\alpha_i}}$ denotes the secondary control input. Hence, the resulting augmented system model with an integrator is now as follows:

$$\dot{\hat{x}}_i(t) = \hat{A}_{ii}\hat{x}_i(t) + \sum_{j \in N_i} \hat{A}_{ij}\hat{x}_j + \hat{B}_i u_i(t)$$
$$+ \hat{G}_i \alpha_i(t) + \hat{M}_i \hat{d}_i(t), \tag{3}$$
$$\hat{y}_i(t) = \hat{x}_i(t),$$
$$\hat{z}_i(t) = \hat{H}_i \hat{x}_i(t), \qquad i = 1, 2, ..., N,$$

where $\hat{x}_i(t) = [x_i^\top(t), \zeta_i^\top(t)]^\top$ is the local state, and $\hat{d}_i(t) = [d_i^\top(t), V_{ref,i}^\top(t)]^\top$ is the exogenous input. The matrices in (3) are given in (Tucci et al., 2015a).

Note that the pair $(\hat{A}_{ii}, \hat{B}_i)$ is controllable, and hence, system (3) is stabilizable.

In the second step, a decentralized output feedback controller is designed to: (i) guarantee stability of the overall microgrid, and (ii) regulate the voltage at each PCC. Towards this end, an output feedback controller is designed as follows:

$$u_i(t) = K_i \hat{y}_i(t) = K_i \hat{x}_i(t), \tag{4}$$

such that $(A_{ii} + B_i K_i)$ is Hurwitz. The knowledge of the dynamics of i-th DGU as well as the power line parameters of the neighboring DGUs are required for designing K_i via Linear Matrix Inequity (LMI) conditions (Tucci et al., 2015b). We now need to make the following two assumptions explicit.

Assumption 1. The current demands for DGUs, i.e., $I_{Li}(t)$, are piece-wise constant which can be changed randomly.

It should be noted that the proposed algorithm does not require to know the current demands for DGUs and Assumption 1 only implies that the current demands can change randomly by in a piece-wise constant fashion.

Distributed ET consensus-based secondary controller: An event-based secondary controller is designed based on a linear discrete-time consensus protocol to achieve current sharing in a DC microgrid. Denoting $\tau_k^i h \subset \mathbb{Z}^+$ as the time instants that events are triggered in the subsystem i, with h as the sampling period, the latest transmitted i-th DGU current signal, $\hat{I}_i(\tau h), \tau \in \mathbb{Z}^+$, is defined as follows:

$$\hat{I}_i(\tau h) = \begin{cases} I_i(\tau_k^i h), & \text{when an event occurs} \\ \hat{I}_i(\tau_k^i h), & \text{otherwise} \end{cases} \tag{5}$$

where $\hat{I}_i(\tau_k^i h)$ is the i-th DGU current at the last event-triggered instant.

To enable some DGUs to exploit the power of the other DGUs for supplying their local loads, the proportional current sharing should be guaranteed. The following control objective is defined for the event-based proportional current sharing of the microgrid.

Control Objective 1. (**Proportional Current Sharing**)

$$\frac{\hat{I}_i(\tau h)}{I_i^s} = \frac{\hat{I}_j(\tau h)}{I_j^s}, \quad (6)$$

where $I_i^s > 0, i = 1, ..., N$ are constant scaling factors proportional to the DGU's generation capacity.

To obtain information sharing and coordination among DGUs, the secondary ET consensus-based controller for the i-th DGU is defined according to the following protocol:

$$\alpha_i((\tau+1)h) = \alpha_i(\tau h) + h[-k_{I,i} \sum_{j \in N_i} a_{ij}(w_i \hat{I}_i(\tau h)$$
$$-w_j \hat{I}_j(\tau h))], \quad (7)$$

where $w_i = \frac{1}{I_i^s}$, and $k_{I,i}$ is the integral coefficient of the i-th DGU.

Note that at the triggering instants τ_k^j, the j-th DGU will communicate with its neighbors and share the value of $I_j(\tau h)$. The secondary control input is then generated using the zero-order hold as follows:

$$\alpha_i(t) = \alpha_i(\tau h), t \in [\tau h, (\tau+1)h). \quad (8)$$

Note that although the i-th DGU has access to its own current $I_i(t)$, the ET consensus-based controller (7) uses the last broadcast current $\hat{I}_i(\tau h)$. This is to ensure that the average of DGUs' initial currents is preserved throughout the evolution of the system.

The subsequent event instants are determined by the event-triggering mechanism, which is given as follows:

$$\tau_{k+1}^i = \inf\{\tau > \tau_k^i : ||I_i(\tau_k^i h) - I_i(\tau h)|| > \sigma_i |\alpha_i(\tau h)|\}, (9)$$

where $\sigma_i > 0$ is a scalar to be designed as a trade off between the network utilization and the control performance. In fact, in order to guarantee the ET-based current sharing in DGUs, the informstion of the currents should be transmitted only when the condition (9) is met.

The error variable between the latest broadcasted current signal and the i-th DGU current is defined as $e_i(\tau h) = \hat{I}_i(\tau h) - I_i(\tau h)$. Note that at time τ_{k+1}^i, a new event is triggered so that the error signal $e_i(\tau h)$ is reset as $e_i(\tau_{k+1}^i h) = 0$. Consequently, the following inequality can be written which holds for all τ:

$$||e_i(\tau h)|| \leq \sigma_i ||\alpha_i(\tau h)||. \quad (10)$$

and it follows that:

$$e^\top(\tau h)e(\tau h) - \alpha^\top(\tau h)\sigma\alpha(\tau h) \leq 0, \quad (11)$$

where $e(\tau h) = [e_1^\top(\tau h), e_2^\top(\tau h), ..., e_N^\top(\tau h)]^\top$, $\alpha(\tau h) = [\alpha_1^\top(\tau h), \alpha_2^\top(\tau), ..., \alpha_N^\top(\tau h)]^\top$, and $\sigma = \mathrm{diag}(\sigma_1, \sigma_2, ..., \sigma_N)$.
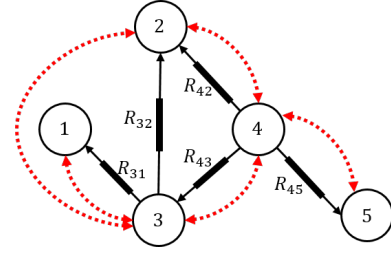

Fig. 2. Physical and communication network of DC microgrid composed of 5 DGUs.

4. STABILITY ANALYSIS AND CURRENT SHARING

In this section, it is shown that the exponential stability of the overall microgrid controlled by utilizing (7) is achieved and the event-based current sharing objective is satisfied. Using the primary controller, the following relationship holds (Tucci et al., 2018):

$$V_i(t) = V_{\mathrm{ref},i} + \alpha_i(t), \quad i = 1, ..., N, \quad (12)$$

Therefore, the dynamics of the overall microgrid is obtained as follows:

$$V(t) = \bar{V}_{ref} + \alpha(t), \quad i = 1, ..., N, \quad (13)$$

where $\bar{V}_{\mathrm{ref}} = [V_{\mathrm{ref},1}, V_{\mathrm{ref},2}, ..., V_{\mathrm{ref},N}]^\top$. The collective dynamics of the secondary ET consensus-based controller for the overall microgrid can be written as follows:

$$\alpha((\tau+1)h) = \alpha(\tau h) + h[-LW(I_t(\tau h) + e(\tau h))]. \quad (14)$$

Given equations (13) and (14) and knowing that the currents vector of DGUs is $I_t(\tau h) = I_L(\tau h) - q_e I_l(\tau h)$ and the vector of line currents is $I_l(\tau h) = -w_e q_e V(\tau h)$, one can get the following relationship:

$$\alpha((\tau+1)h) = \alpha(\tau h) + h[-Q\alpha(\tau h) - LWe(\tau h)$$
$$-LWI_L(\tau h) - Q\bar{V}_{ref}], \quad (15)$$

where $Q = LWM$ and $M = q_e w_e q_e^\top$. The following system is considered for the stability analysis of the linear system (15):

$$\alpha((\tau+1)h) = A'\alpha(\tau h) - B'e(\tau h), \quad (16)$$

where $A' = (1 - hQ)$, and $B' = hLW$.

Theorem 1. Consider the system (2) subject to the ET protocol (7). It follows that under Assumption 1 all DGUs can achieve current sharing under the triggering condition (9) and the overall microgrid is stable if there exist a symmetric positive-definite matrix $P \in \mathbb{R}^{N \times N}$, and a matrix $\sigma \in \mathbb{R}^{N \times N}$, such that the following LMI holds:

$$\begin{bmatrix} A'^T PA' - P + \sigma & -A'^T PB' \\ -B'^T PA' & -I + B'^T PB' \end{bmatrix} < 0, \quad (17)$$

Proof. First the current sharing objective is shown. The distributed controller (7) leads to current sharing at the steady state which can be expressed as follows:

$$0 = -k_{I,i} \sum_{j \in N_i} a_{ij}(w_i \hat{I}_i(\tau h) - w_j \hat{I}_j(\tau h)), \quad (18)$$
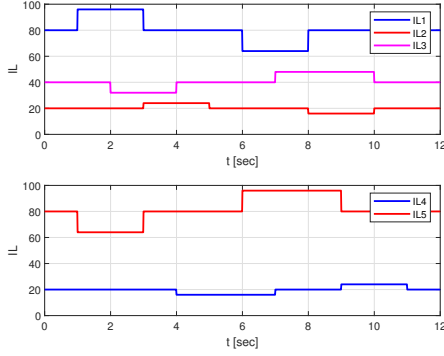
which is equivalent to:

Fig. 3. The local load currents of the DGUs 1-5.

$$0 = -k_{I,i} \sum_{j \in N_i} a_{ij}[w_i(I_i(\tau h) + e_i(\tau h)) - w_j(I_j(\tau h) + e_j(\tau h))],$$

which can compactly be expressed for all DGUs as follows:

$$0 = -K_I L_c W \bar{I} - K_I L_c W e(\tau h), \tag{19}$$

where $K_I = \text{diag}(k_{I,1}, k_{I,2}, ..., k_{I,N})$, $W = \text{diag}(\frac{1}{I_1^s}, ..., \frac{1}{I_N^s})$ and $\bar{I} = [\bar{I}_1, \bar{I}_2, ..., \bar{I}_N]^\top$.

Note that $\bar{I}$ is the steady state solution of $I(\tau h) = [I_1(\tau h), I_2(\tau h), ..., I_N(\tau h)]^\top$. Equation (19) can be expressed as follows:

$$0 = -LW(\bar{I} + e(\tau h)). \tag{20}$$

where $L = K_I L_e$ denotes the Laplacian matrix of $\mathcal{G}_e$ with w_e replaced by $K_I w_e$.

According to the properties of the Laplacian matrix, it is concluded from (20) that $W(\bar{I} + e(\tau h)) \in \mathcal{R}(\mathbb{1})$, where $\mathcal{R}(\mathbb{1})$ denotes the range of $\mathbb{1}$, i.e., all elements of $W(\bar{I} + e(\tau h))$ are identical. Therefore it is shown that (6) is satisfied and the event-based proportional current sharing is achieved.

Now the stability analysis of the overall microgrid is shown. System (16) is stable if there exists a discrete quadratic Lyapunov function $S_a(\tau h) = \alpha^\top(\tau h) P \alpha(\tau h)$ with $P > 0$ such that the following equation holds:

$$S_a((\tau+1)h) - S_a(\tau h) = \alpha^\top((\tau+1)h) P \alpha((\tau+1)h)$$
$$-\alpha^\top(\tau h) P \alpha(\tau h) < 0 \tag{21}$$

Considering the event-triggering condition (11), the sufficient condition for satisfying (21) is obtained by the following Linear Matrix Inequality (LMI):

$$\alpha^\top((\tau+1)h) P \alpha((\tau+1)h) - \alpha^\top(\tau h) P \alpha(\tau h) - e^\top(\tau h)e(\tau h)$$
$$+\alpha^\top(\tau h)\sigma\alpha(\tau h) < 0. \tag{22}$$

Substituting (16) into (22) and after some algebraic manipulations, the LMI (17) is achieved. This completes the proof of the theorem. $\square$

Remark 1 It should be emphasized that the proposed event-triggered secondary controller is implemented in a discrete-time framework and hence there is no need to consider Zeno phenomena while the previous works in Pullaguram et al. (2018); Han et al. (2017) proposed continuous-time event-triggered controllers without investigating the existence of Zeno phenomena. The main challenge for the continuous-time framework is that in current
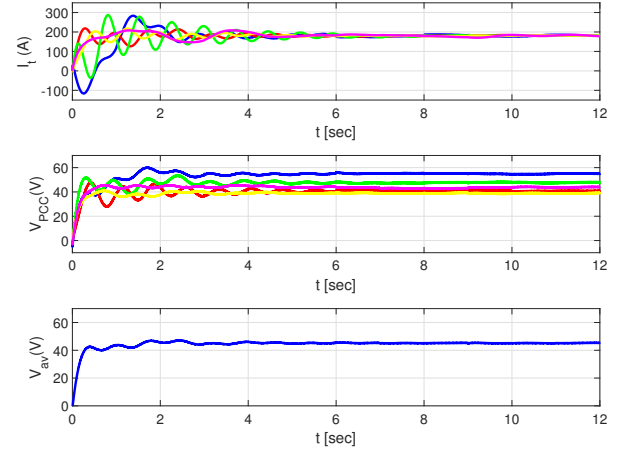

Fig. 4. The voltage regulation, current sharing, and the average PCCs voltage of DGUs.

sharing controller the even-triggered mechanism depends on only the current of DGU, i.e. I_i while generally it should depend on all the states of the DGU, i.e I_i and V_i.

5. SIMULATION RESULTS

In this section, simulation results are presented to demonstrate the efficiency of the proposed distributed discrete-time ET consensus-based control for current sharing and voltage stabilization of DC microgrids.

A microgrid composed of 5 DGUs is considered in Fig. 2. It can be noted in Fig. 2 that the physical and communication graphs are considered as directed and undirected, respectively. DGUs scaling factors are $I_1^s = 1, I_2^s = 4, I_3^s = 2, I_4^s = 4, I_5^s = 1$, and the voltage reference of DGUs is set to $\bar{V}_{\text{ref}} = [40, 50, 48, 42, 46]^\top$. The piece-wise constant load currents of the DGUs 1-5 are considered in Fig. 3. The electrical parameters of the DGUs and the primary controller gains are given in Tables 2 and 3 in (Tucci et al., 2016). The sampling period and the secondary discrete-time ET-based controller gains are considered as $h = 0.01$ and $K_I = \text{diag}(0.1, 0.1, 0.05, 0.05, 0.1)$, respectively. The matrix σ is obtained by solving the LMI (17) which leads to $\sigma = \text{diag}(0.243, 0.244, 0.243, 0.245, 0.242)$. The communication links between the connected DGUs are considered as $\frac{1}{R_{ij}}$.

Voltage regulation, current sharing, and average PCCs voltage of DGUs are depicted in Fig. 4. The overall microgrid is stable via primary controllers and the current sharing is achieved by the discrete-time ET consensus-based controller. It is also shown that the voltage balancing is also guaranteed and the average PCCs voltages are the same at steady state.

It can be concluded from the simulation results that the data transmission rates of the currents are reduced by 16.73%, 41.38%, 90.25%, 55.20%, and 38.47% for the DGUs 1 to 5, respectively. This implies that the broadcast currents of the DGUs do not update continuously and the data exchanges are reduced which shows the ability of the event-triggering scheme in adjusting the broadcast periods.

6. CONCLUSION

In this paper, a distributed discrete-time ET consensus-based controller for a DC microgrid that is composed of multiple DGUs is designed. The proposed ET based controller achieves current sharing and reduces the communication rate of the network objectives that would improve the network security and reduce the communication cost. The proposed event-triggered secondary controller is implemented in a discrete-time framework and hence there is no need to consider the Zeno phenomena. Stability of the overall microgrid using this hierarchical control scheme is shown quantitatively by Lyapunov stability theory. In future work, the problem of the secure current sharing in presence of the DOS attack will be investigated.

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