International Journal of Industrial Electronics, Control and Optimization © 2021 IECO
Vol. *, No. *, pp. *-*, * (2021)

A New Event-Triggered Consensus Control for Microgrids

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ABSTRACT

This paper studies an adaptive event-triggered consensus problem for heterogeneous multi-agent systems considering the time delay of the communication network. An event-triggered interval is here considered as a specific delay and unified round trip time (RTT) delay. Furthermore, an efficient optimal predictive-based coordination control strategy is introduced for balancing the non-ideal behaviors of communication channels. The efficiency of the proposed method for controlling network-based multi-agent systems with coupled subsystems is evaluated in two stages. In the first stage, the very method is implemented on two coupled continuous stirred tank reactors while in the second one, it is used to control the voltage and current of a DC microgrid consisting of several distributed generation units. To prevent the unessential utilization of communication resources, the transfer of information does not occur in this mechanism unless a specific event is triggered. The simulation results show that despite being non-ideal and time-delayed communication channels, the proposed technique is capable of improving the performance of power grids.

Article Info

Keywords:
Adaptive event-triggered control, Microgrids, Multi-agent systems, Network-based control system, Time delay

Article History:
Received 2020-11-30
Accepted 2021-06-29

I. INTRODUCTION

Today, because of the tendency to replace renewable energy sources with fossil fuels and also the appearance of different distributed generation sources, traditional electric grids are rapidly changing with the use of microgrids because, in addition to providing their own loads with their DGs, microgrids can support the main grid during peak hours when the grid load increases sharply and the heavy loading disrupts the power grid [1]. Microgrids are controllable units composed of distributed generation sources, loads, energy storage sources, and control devices that are interconnected by power lines [2]. They are generally divided into three categories: Alternative Current (AC), Direct Current (DC), and hybrid AC-DC [3]. The standard microgrid model used for residential, commercial, and industrial applications is AC. Although DC power systems cannot solve some challenges of AC microgrids such as reactive power management, frequency control, synchronization, etc., they exhibit such advantages as availability of efficient converters, appropriate interfacing of batteries and DC energy sources, minimal power losses, and an ever-growing number of DC loads, making this type of microgrids attractive [4-7].

Current sharing and voltage regulation are the two main control challenges of DC microgrids. The optimal voltage regulation strategy leads to the desired output voltage of each microgrid while the other strategy, called the current sharing control strategy, causes the current to be equally distributed among all microgrids [8]. Hierarchical control has been proposed in several articles for these two purposes [9]. Although centralized controllers have a constant voltage and suitable current distribution, when the size of the grid increases, the grid load will also greatly increase and a failure in a single point may lead to the malfunction of the entire grid [10]. This is the main reason for the preference of decentralized and distributed controllers over centralized ones.

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Droop controllers as a communication-less method may lead to voltage deviation from the reference value. Therefore, Zhao and Dörfler [11] combined a secondary control layer with consensus algorithms with a droop controller to control voltage deviations. In distributed control, each subsystem can receive information from its neighbors. This feature can improve system performance and has made many researchers interested in using scalable control strategies, especially for splitting current [11-14]. Despite the benefits of distributed controls, the exchange of information between subsystems on large networks may create a heavy communication burden in the communication network. To prevent unnecessary use of communication resources and reduce the frequency of information transmission and save energy consumption, event-triggered control (ETC) techniques have been introduced in recent researches [15-18]. In these techniques, each subsystem transmits its information according to certain event-triggering conditions via the communication network and the data transmission will only be done when the event-triggering condition occurs. So, communication costs are significantly reduced in these approaches [19]. Han et al. [20] proposed a distributed nonlinear ETC scheme for the current sharing and voltage regulation on an electrical grid model with a DC microgrid.

Research on ETC technology has proposed an efficient method called Adaptive Event Trigger Control (AETC) [21-25]. In these approaches unlike traditional ETC algorithms, some control parameters are adjusted according to the line signal to reduce the method's conservativeness. In the field of MASs, many have been conducted AETC. For example, Zou and Xiang [26] investigated the arrangement control for networked MASs by AETC. Yang et al. [27] examined the issue of the consensus for MASs by combining AETC with predictive control methods. Especially, in heterogeneous MASs, the output consensus problem and also a fully distributed ETC strategy with an AETC are presented in [21].

In most of the research works reviewed, some important behavior in the networked HMASs, such as the strong interaction among subsystems, is not taken into account in the design of adaptive event-triggered consensus controllers. Moreover, the impact of network latency on the communication connections among subsystems is another significant aspect in networked HMASs rarely considered in the literature.

Little work on the design of network-based multifactor power system controllers has considered the non-ideal behavior of the telecommunication network in interconnected communications between subsystems, which is another motivation for the present study.

Furthermore, new industrial distributed systems are regarded as large multi-agent systems. So, the challenging problems listed for network-based multi-agent systems occur in network-based distributed systems integrated with coupled sub-system [22]. Since few studies have been conducted on the design of network-based multi-agent power system controllers with considering the non-ideal behavior of the telecommunication network in interconnected communications among subsystems, it can be accounted as another motivation for the present research. Another goal of the present work is to examine the control of network-based interconnected systems via the proposed approach. In this regard, in the first case study, the proposed method is applied to two connected stirred tank reactors with subsystems strongly connected while in the second case, a DC microgrid model including various DG units and state-space model is considered to achieve the benefits of reducing network communication costs and improving security by controlling the voltage and current of DGs by the proposed adaptive event-triggered consensus controller. The main sections are as follows:

i) Proposing an AETC scheme for discrete-time MASs besides an adaptive event-triggered communication scheme to reduce the frequency of data transmission.

ii) Developing an efficient PD-like optimal control protocol for heterogeneous MASs as well as designing a PD-like predictive controller.

iii) Deriving the stability condition of network-based MASs considering random round-trip time (RTT) delays.

iv) Implementing the proposed method onto two connected stirred tank reactors with subsystems strongly connected for confirming the efficiency of the very approach.

v) Implementing the proposed method on a DC microgrid with five distributed generation units for gaining the proposed method advantages besides controlling the voltage and current of the microgrid.

The rest of this paper is organized as follows. Section II introduces the model of the studied system with some necessary assumptions and definitions. Section III presents the new event-triggered conditions besides the proposed PD-like predictive control scheme and the stability and consensus are analyzed for whole systems. Finally, the simulation verification and the conclusions are provided in Sections IV and V, respectively.

II. PROBLEM FORMULATION

The general linear discrete-time description of MASs can be considered as follows:

$$x_i(k+1) = H_i x_i(k) + G_i u_i(k+1) \tag{1}$$

where $x_i(k)$ and $u_i(k)$are the states and inputs of the ith agent, respectively and H_i and G_i are the system matrices of the ith agent, respectively.

Before proceeding, it is necessary to express some assumptions and definitions as bellow:

Assumption 1: The pair (H_i, G_i) is controllable and the states can be measurable.

Assumption 2: The communication delay is bounded via τ_{max}, and the maximum amount of event-triggered time interval is δ_{max} [28].

Definition 1: The consensus problem of HMASs is that the different subsystems keep the consensus of the states while reducing the data transmission frequency and considering networks' constraints, i.e.

$$\lim_{k\to\infty}\left|x_i(k)-x_j(k)\right|=0 \tag{2}$$

According to the definition of ETC, the controller will be in the following form:

$$u_i(k)=u_i\left(k_t^i\right),k\in\left\lfloor k_t^i,k_{t+1}^i\right) \tag{3}$$

where k_t^i is the triggering time of the ith agent, and k_{t+1}^i stands for the next event-triggered time. We have:

$$k_{t+1}^i=inf\{k:k>k_t^i,g_i(k)>0\} \tag{4}$$

where $g_i(k)=e_i^T(k)We_i(k)-R_i(k)x_i^T(k)Wx_i(k)$, which is explained in the next section.

III. MAIN RESULTS

A. The Developed Adaptive Event-Triggered Based Control

In the following, two adaptive event-triggered techniques are developed to store the communication network bandwidth or energy. Commonly, if the ratio of state error of the ith agent to its current state will be greater than a predefined value, the state data can be transferred. However, in the MASs' network topology, there is a high probability that only event-triggered mechanisms exist between agents, not the agent itself. Thus, an adaptive event-trigger control (AETC) is developed in this paper based on the states of entire agents.

Case 1: The proposed adaptive event-triggered strategy is as follows:

$$e_i^T(k)We_i(k)>R_i(k)x_i^T(k)Wx_i(k) \tag{5}$$

$$R_i(k)=\frac{R_i(k-1)}{1+e_i^T(k)We_i(k)} \tag{6}$$

where $e_i(k)=x_i(k)-x_i\left(k_t^i\right)$..

Lemma 1. For the condition (5) and the initial values $R_i(0)\in(0{,}1)$, the following inequality is satisfied for all $k\in N$

$$0\le R_i(k)\le R_i(0)<1 \tag{7}$$

Proof: To prove, firstly, consider $k=1$, thus we have:

$$R_i(1)=\frac{R_i(0)}{1+e_i^T(1)We_i(1)}\le R_i(0) \tag{8}$$

Then, given $k>1$, the quadratic term $e_i^T(k)We_i(k)$ in Equ. (5) will be semi-definite, i.e., $e_i^T(k)We_i(k)\ge 0$. As a result, we have:

$$R_i(k)=\frac{R_i(k-1)}{1+e_i^T(k)We_i(k)}\le R_i(k-1) \tag{9}$$

which results in $0\le R_i(k)\le R_i(0)<1$ if one chooses the appropriate $R_i(0)$. So, the proof is completed.

Case 2: In the research of ETC, the objects are usually network-based control systems, whose controllers are connected with sensors and actuators through non-ideal communication channels. However, in most MASs, the state of the agent itself can be obtained in real-time, and the state of the neighbor agent is transferred via the communication network. Only event-triggered communication between agents is considered. As a result, the triggering condition (5) is not suitable and appropriate for this case and a new efficient condition for this case is developed as follows:

$$e_{ij}^T(k)We_{ij}(k)>R_{ij}(k)x_j^T(k)Wx_j(k) \tag{10}$$

$$R_{ij}(k)=\frac{R_{ij}(k-1)}{1+e_{ij}^T(k)We_{ij}(k)} \tag{11}$$

where $e_{ij}(k)=x_i(k)-x_i\left(k_t^{ij}\right)$ and k_t^{ij} are the triggering communication time from the ith agent to the jth agent. It is clear that the triggering condition of case 2 becomes condition (5) if $i=j$. In other words, condition (5) is a special case of condition (10).

B. The PD-like Predictive Controller

The proposed method is a combination of the PD control based on predictors. Since predictors are used to simultaneously estimate the delayed states, the use of the delayed information is avoided. Thus, the performance degradation due to communication time delay can be alleviated. In this regard, to achieve consensus among heterogeneous agents modelled by deferent systems, an optimal coordination control protocol, which consists of two parts, is proposed. The first part is the proportional part, which can be obtained by various methods, such as pole placement, LQR, and so on [29]. The second part is the predictive term, which is to be designed as follows.

Consider the following controller:

$$u_i(k)=K_ix_i(k)+v_i(k) \tag{12}$$

where K_i is the proportional parameter matrix and $v_i(k)$ is the optimal prediction of the controller. By substituting Equ.

(12) in Equ. (1), we obtain:

$$x_i(k+1) = (H_i + G_iK_i)x_i(k) + G_iv_i(k) \tag{13}$$

To calculate the prediction term $v_i(k)$, the following cost function is introduced.

$$\sum g_{ij}\left(x_i(k+1) - x_j(k+1)\right)^2 + c_i{v_i}^2(k) \tag{14}$$

where $\Gamma = [g_{ij}]$ is the adjacency matrix, $g_{ij} = 1$ if $i \neq j$, otherwise $g_{ij} = 0$. Also, c_i denotes the weighting factor.

The minimization of the cost function (14) leads to:

$$\frac{\partial \sum_{i=1}^{N} J_i(k)}{\partial v_i(k)} = 0 \tag{15}$$

By substituting the relevant formulas in the formulas (15), we obtain:

$$\begin{gathered} G_i^T \textstyle\sum_{j=1}^{N} g_{ij}\left(x_i(k+1) - x_j(k+1)\right) - \\ G_i^T \textstyle\sum_{j=1, j\neq i}^{N} g_{ij}\left(x_j(k+1) - x_i(k+1)\right) + \\ c_iv_i(k) = 0 \end{gathered} \tag{16}$$

Furthermore, the above formula can be rewritten as follows:

$$\begin{gathered} G_i^T \textstyle\sum_{j=1}^{N} g_{ij}\Big((H_i + G_iK_i)x_i(k) + G_iv_i(k) - \\ (H_j + G_jK_j)x_j(k) - G_jv_j(k)\Big) - \\ G_i^T \textstyle\sum_{j=1, j\neq i}^{N} g_{ji}\Big((H_j + G_jK_j)x_j(k) + G_jv_j(k) - \\ (H_i + G_iK_i)x_i(k) - G_iv_i(k)\Big) + c_iv_i(k) = 0 \end{gathered} \tag{17}$$

Merging the same items leads to

$$\begin{gathered} G_i^T \textstyle\sum_{j=1}^{N} g_{ij}\Big(G_iv_i(k) - \\ G_iv_j(k)\Big) + G_i^T \textstyle\sum_{j=1, j\neq i}^{N} g_{ji}\Big(G_iv_i(k) - \\ G_iv_j(k)\Big) + c_iv_i(k) = -\Big(G_i^T \textstyle\sum_{j=1}^{N} g_{ij}\Big((H_i + \\ G_iK_i)x_i(k) - (H_j + G_jK_j)x_j(k)\Big) + \\ G_i^T \textstyle\sum_{j=1, j\neq i}^{N} g_{ji}\Big((H_i + G_iK_i)x_i(k) - (H_j + \\ G_jK_j)x_j(k)\Big)\Big) \end{gathered} \tag{18}$$

Moreover, the following form can be obtained.

$$\sum_{j=1}^{N} b_{ij}v_i(k) = -\sum_{j=1}^{N} a_{ij}x_i(k) \tag{19}$$

Where

$\omega = \sum_{j=1}^{N} g_{ij} + \sum_{j=1, j\neq i}^{N} g_{ji}$, $b_{ii} = \omega G_i^T G_i + c_iI_{ii}$, $b_{ij} = -(g_{ij} + g_{ji})G_i^T G_j$, $a_{ii} = \omega G_i^T(H_i + G_iK_i)$, $a_{ij} = -(g_{ij} + g_{ji})G_i^T(H_i + G_jK_j)$.

Furthermore, we have the matrix I_{ii} in which the element of the ith row and ith column is one and other elements are zero.

The compact form of the above formula can be written as follows:

$$Bv(k) = -Ax(k) \tag{20}$$

where $B = \{b_{ij}\}$ and $A = \{a_{ij}\}$.

Then, the prediction term of the controller for the whole systems is

$$v(k) = -B^{-1}Ax(k) \tag{21}$$

where

$v(k) = [v_1^T(k)\ v_2^T(k) \ldots v_N^T(k)]^T$, $x(k) = [x_1^T(k)\ x_2^T(k) \ldots x_N^T(k)]^T$

For the agent i, the prediction of the controller is as follows:

$$v_i(k) = I_{ii}v(k) = -I_{ii}B^{-1}Ax(k) \tag{22}$$

Then, the controller law (12) can be rewritten as

$$\begin{aligned} u_i(k) &= K_ix_i(x) + v_i(k) \\ &= K_ix_i(x) - I_{ii}B^{-1}Ax(k) \end{aligned} \tag{23}$$

According to the structure of the agent and its communication strategy, the controller law is obtained with the ETC.

$$u_i(k) = K_ix_i(x) + v_i(k_t^i), \qquad k \in \left|k_t^i, k_{t+1}^i\right) \tag{24}$$

Since the introduction of the network may cause delays in communication between agents, a PD-like predictive controller is proposed to actively compensate for the delay and achieve the consensus eventually. Combining Equ. (13) and Equ. (24), the predictions of state are given as

$$\begin{aligned} \hat{x}_i\left(k_t^i + 1 \middle| k_t^i\right) &= (H_i + G_iK_i)\hat{x}_i\left(k_t^i \middle| k_t^i\right) \\ &\quad + G_i\hat{v}_i\left(k_t^i \middle| k_t^i\right) \\ &= (H_i + G_iK_i)\hat{x}_i\left(k_t^i \middle| k_t^i\right) \\ &\quad + G_iI_{ii}B^{-1}A\hat{x}\left(k_t^i \middle| k_t^i\right) \end{aligned} \tag{25}$$

Which can be described in an aggregated form as Equ. (26).

$$\begin{aligned} \hat{x}_i\left(k_t^i + 1 \middle| k_t^i\right) &= \widetilde{H}\hat{x}\left(k_t^i \middle| k_t^i\right) - \tilde{G}B^{-1}H\hat{x}\left(k_t^i \middle| k_t^i\right) \\ &= \phi\hat{x}\left(k_t^i \middle| k_t^i\right) \\ \hat{x}_i\left(k_t^i + d(k) \middle| k_t^i\right) &= \phi\hat{x}\left(k_t^i + d(k) - 1 \middle| k_t^i\right) \\ &= \phi^{\bar{\tau}}\hat{x}\left(k_t^i \middle| k_t^i\right) \\ \hat{x}_i\left(k_t^i + \bar{\tau} + \bar{p} \middle| k_t^i\right) &= \phi\hat{x}\left(k_t^i + \bar{\tau} + \bar{p} - 1 \middle| k_t^i\right) \\ &= \phi^{\bar{\tau}+\bar{p}}\hat{x}\left(k_t^i \middle| k_t^i\right) \end{aligned} \tag{26}$$

Where

$\hat{x}_i\left(k_t^i \middle| k_t^i\right) = x_i\left(k_t^i \middle| k_t^i\right) = x_i(k_t^i)$, $\hat{v}_i\left(k_t^i \middle| k_t^i\right) = v_i(k_t^i)$, $\widetilde{H} = diag(\overline{H}_1\ \overline{H}_2 \ldots \overline{H}_N)$, $\tilde{G} = diag(\bar{G}_1\ \bar{G}_2 \ldots \bar{G}_N)$, $\overline{H}_i = H_i + G_iK_i$, $\phi = \widetilde{H} - \tilde{G}B^{-1}A$ and $\bar{\tau}$ are the upper bound of the communication delay.

We design a function to denote the relationship between the current time, trigger time, and delay. In the suggested scheme, the event-triggered time interval is considered a particular delay and included in the round-trip time (RTT) delay.

$$k_t^i = k - \tau(k) - l = k - d(k) l = 0,1,\dots,\bar{p} \tag{27}$$

where $\bar{p}$ is the upper bound of the event-triggered interval.

Afterward, the prediction part of the controller of agent i can be expressed as

$$\begin{aligned}
\hat{v}_i\left(k_t^i + 1 \middle| k_t^i\right) &= -I_{ii} B^{-1} H \hat{x}\left(k_t^i + 1 \middle| k_t^i\right) \\
&\vdots \\
\hat{v}_i\left(k_t^i + d(k) \middle| k_t^i\right) &= -I_{ii} B^{-1} H \hat{x}\left(k_t^i + d(k) \middle| k_t^i\right) \\
&\vdots \\
\hat{v}_i\left(k_t^i + \bar{\tau} + \bar{p} \middle| k_t^i\right) &= -I_{ii} B^{-1} H \hat{x}\left(k_t^i + \bar{\tau} + \bar{p} \middle| k_t^i\right)
\end{aligned} \tag{28}$$

Based on the trigger condition and (27), we can easily get

$$\hat{v}_i\left(k_t^i + \tau(k) + l \middle| k_t^i\right) = \hat{v}_i(k | k - d(k)) \tag{29}$$

Then, the PD-like predictive controller is

$$u_i(k) = K_i x_i(k) + \hat{v}_i(k | k - d(k)) = K_i x_i(k) + I_{ii} B^{-1} A \phi^{d(k)} x\left(k_t^i \middle| k_t^i\right) \tag{30}$$

After that, the purpose is to find the stability condition and design the suitable controller so that the above systems become ultimately stable and achieve the consensus among agents.

According to the structure of the control system we designed, the current state $x_i(k)$ is available, i.e. $\hat{x}_i\left(k_t^i + \bar{\tau} + \bar{p} \middle| k_t^i\right) = x(k)$, then

$$x_i(k+1) = \bar{H}_i x_i(k) + G_i \hat{v}_i(k | k - d(k)) = \bar{H}_i x_i(k) + G_i I_{ii} B^{-1} A \phi^{d(k)} x\left(k_t^i \middle| k_t^i\right) \tag{31}$$

The compact form can be written as

$$x(k+1) = \tilde{H} x(k) - \tilde{G} B^{-1} A \phi^{d(k)} \hat{x}\left(k - d(k)\right) \tag{32}$$

Moreover, the compact form predictions of the state is that

$$\begin{aligned}
\hat{x}(k) &= \tilde{H} \hat{x}(k-1) - \tilde{G} B^{-1} A \hat{x}(k-1) \\
&\vdots \\
\hat{x}(k + d(k) + 1) &= \tilde{H} \hat{x}\left(k - d(k)\right) - \tilde{G} B^{-1} A \hat{x}\left(k - d(k)\right) \\
&\vdots \\
\hat{x}(k - \bar{\tau} - \bar{p} + 1) &= H \hat{x}(k - \bar{\tau} - \bar{p}) - \tilde{G} B^{-1} A \hat{x}(k - \bar{\tau} - \bar{p})
\end{aligned} \tag{33}$$

Equ. (32) and Equ. (33) can be expressed as

$$X(k+1) = \Lambda X(k) \tag{34}$$

Where

$$(k) = \begin{bmatrix} x(k) \\ \hat{x}(k-1) \\ \vdots \\ \hat{x}\left(k - d(k)\right) \\ \hat{x}(k - \bar{\tau} - \bar{p}) \end{bmatrix},$$

$$\Lambda = \begin{bmatrix}
\widetilde{H} & 0 \cdots & \tilde{G} B^{-1} A \phi^{d(k)} & 0_{Nn \times (\bar{\tau} - \bar{p} - d(k)) Nn} \\
0 & \phi \ \cdots & 0 & 0_{Nn \times (\bar{\tau} - \bar{p} - d(k)) Nn} \\
\vdots & \vdots \ \ddots & \vdots & \vdots \\
0 & 0 \ \cdots & \phi & 0_{Nn \times (\bar{\tau} - \bar{p} - d(k)) Nn} \\
0 & 0 \ \cdots & 0 & \phi_{0_{\bar{\tau} - \bar{p} - d(k)}}
\end{bmatrix}$$

Theorem 1. The stability and consensus performance of systems (34) is achieved if the Eigenvalues of matrix Λ are within the unit circle.

Proof: For a stochastic switching system, each sub-matrix of its systems' matrix is stable, then the whole system is stable [30]. Using the pole placement approach and the presented method we can choose the suitable $\mathrm{K_i}$ such that $\bar{H}_i = H_i + G_i K_i$ will be stable, Thus, as $\emptyset = \bar{H} - \tilde{G} B^{-1} A$, it makes that the Eigenvalues of matrix $\emptyset$ will be within the unit circle. As a result, all sub-matrixes of Λ are stable, and then the system can be ensured to be stable. The proof is completed.

IV. SIMULATION STUDIES

Here, we consider two coupled continuous stirred tank reactors (CSTRs) as a case study. The nonlinear dynamic description of the CSTR model is considered as described in [31]. Moreover, the value of process parameters and operating steady states are given in Table I. The system has two coupled sub-systems that are interacted through their states. The sampling interval is chosen as $T_s = 0.0025\,h$. As a result, the nominal discrete-time linear state-space can be presented in the following form:

$$\begin{aligned}
\bar{x}_{k+1}^1 &= A^{11} \bar{x}_k^1 + B^1 u_k^1 + A^{12} \bar{x}_k^2, \qquad \bar{y}_k^1 = C^1 \bar{x}_k^1 \\
\bar{x}_{k+1}^2 &= A^{22} \bar{x}_k^2 + B^2 u_k^2 + A^{21} \bar{x}_k^1, \qquad \bar{y}_k^2 = C^2 \bar{x}_k^2
\end{aligned} \tag{35}$$

Where

$\bar{x}_k^1 = \begin{bmatrix} \frac{T_1 - {T_1}^S}{{T_1}^S} \\ \frac{C_{A_1} - C_{A1}^S}{C_{A1}^S} \end{bmatrix}$, $\bar{x}_k^2 = \begin{bmatrix} \frac{T_2 - {T_2}^S}{{T_2}^S} \\ \frac{C_{A_2} - C_{A2}^S}{C_{A2}^S} \end{bmatrix}$, $u_k^1 = \begin{bmatrix} \frac{Q_{r1} - Q_{r1}^S}{Q_{r1}^S} \\ \frac{C_{A0} - C_{A0}^S}{C_{A0}^S} \end{bmatrix}$, $u_k^2 = \begin{bmatrix} \frac{Q_{r2} - Q_{r2}^S}{Q_{r2}^S} \\ \frac{C_{A03} - C_{A03}^S}{C_{A03}^S} \end{bmatrix}$, $A^{11} = \begin{bmatrix} 1.0488 & 0.0117 \\ -0.1614 & 0.8786 \end{bmatrix}$, $A^{12} = \begin{bmatrix} 0.0920 & 0.0007 \\ -0.0093 & 0.0895 \end{bmatrix}$, $B^1 = \begin{bmatrix} 0.0036 & 0.0002 \\ -0.0003 & 0.0281 \end{bmatrix}$, $C^1 = [1 \quad 0]$, $A^{22} = \begin{bmatrix} 0.9113 & 0.0026 \\ -0.0359 & 0.8706 \end{bmatrix}$, $A^{21} = \begin{bmatrix} 0.0870 & 0.0006 \\ -0.0081 & 0.0714 \end{bmatrix}$, $B^2 = \begin{bmatrix} 0.0029 & 0.0001 \\ -0.0001 & 0.0567 \end{bmatrix}$, $C^2 = [1 \quad 0]$.

In addition, an additive state disturbance is considered as

$w_k^i \in \mathbb{W}^i$ where $\mathbb{W}^i = \{w^i \subseteq \mathbb{R}^2 ||w^i|_\infty \le 0.01\}$ and the output disturbance is $v_k^i \in \mathbb{V}^i$ where $\mathbb{V}^i = \{v^i \subseteq \mathbb{R}^1 ||v^i|_\infty \le 0.01\}$.

TABLE I

DEFINITIONS OF PROCESS VARIABLES

Variable	Definition
$F_0,\ F_r,\ F_3$	Flow rate of fresh A, flow rate of recycled A from reactor 2, flow rate of additional fresh stream feeding pure A
F_1, F_2	Effluent flow rate from reactors 1, 2
$C_{A1},\ C_{A2}$	Molar concentration of A in reactors 1, 2
T_1, T_2	Temperatures in reactors 1, 2
T_0, T_{03}	Feed stream temperatures to reactors 1, 2
Q_{r1}, Q_{r2}	Heat input rate into reactors 1, 2
$C_{A0},\ C_{A3}$	Inlet reactant concentration of reactors 1, 2
V_1, V_2	Reactor volume of reactors 1, 2
$\Delta H_j,\ k_j,\ E_j$ for $j = 1,2,3$	Enthalpies, pre-exponential constants, and activation energies of the three reactions
ρ_s, R, c_p	Heat capacity, gas constant, and density of fluid in the reactor

The induced time-varying delays of communication channels, which connect the local control units of two CSTRs to each other, are created randomly between 1 and 14 time steps (i.e., 126 seconds). The main objective of the designed control scheme is to regulate the system to the unstable (open loop) steady-state employing the suggested approach. The initial state for the system is chosen as $(537.3704\,, 0.8342\,, 340.0798, 3.5519)^{\mathrm{T}}$. Moreover, the simulation horizon is considered 0.6 hour.

In the following, some simulations are done to compare the proposed method and a resilient event-triggered output feedback control approach developed in [32] and two AETC schemes adopted from [20] and [22]. Furthermore, Q_{r1}, Q_{r2}, C_{A0} and C_{A03} are assumed to be constrained by $|Q_{r1}| \le 1.4 \times 10^6 kJ/h$, $|Q_{r2}| \le 1.8 \times 10^6 kJ/h$, $0 \le C_{A0} \le 6 kmol/m^3$ and $0 \le C_{A03} \le 4\ kmol/m^3$, respectively. Moreover, the random induced delays of communication channels connecting the local control units of subsystems are changing between 1 to 14 steps. The initial state $(T_1^0\,(K), C_{A1}^0(kmol/m^3), T_2^0(K),\ C_{A2}^0(kmol/m^3))^T$ for the plant is chosen as $(412.9470\,, 1.8367\,, 384.4043, 1.5951)^{\mathrm{T}}$. In all simulation studies, the initial conditions are the same and the simulation horizon is considered as one hour.

The trajectories of state obtained via the suggested approach and other approaches adopted from [32], [21], and [23] are depicted in Figs. 1-4. Moreover, the trajectories of input obtained via the suggested approach and other approaches adopted from [32], [21], and [23] are depicted in Figs. 5-8. As can be concluded from these figures, the proposed method gives a more appropriate performance of stability and consensus in comparison to other applied approaches.

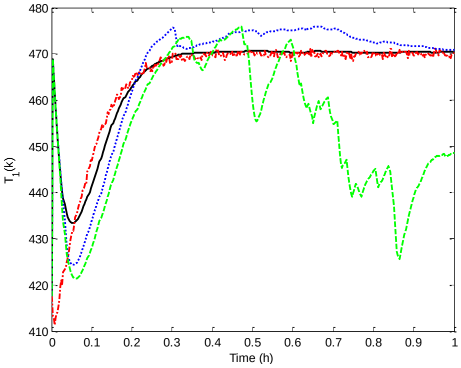

Fig. 1. The trajectories of state of the closed-loop system obtained via the suggested approach (solid lines) and resilient event-triggered output feedback control [32] (dashed-dotted lines), AETC approach presented in [21] (dotted lines), and AETC approach presented in [23] (dashed lines).

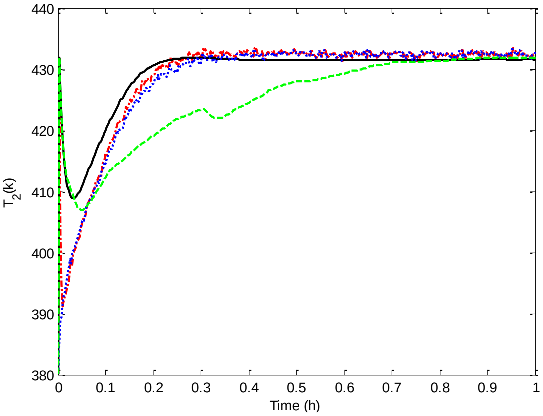

Fig. 2. The trajectories of state of the closed-loop system obtained via the suggested approach (solid lines) and resilient event-triggered output feedback control [32] (dashed-dotted lines), AETC approach presented in [21] (dotted lines), and AETC approach presented in [23] (dashed lines).

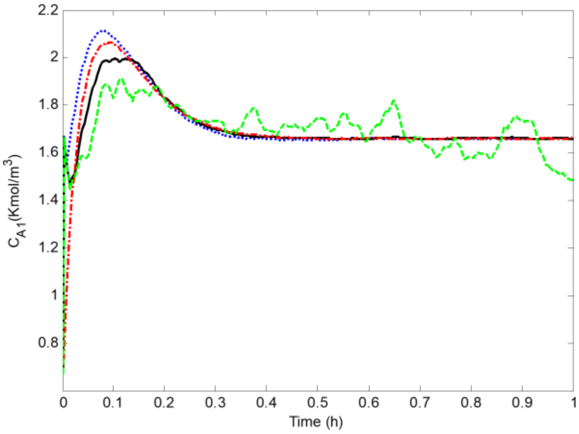

Fig. 3. The trajectories of state of the closed-loop system obtained via the suggested approach (solid lines) and resilient event-triggered output feedback control [32] (dashed-dotted lines), AETC approach presented in [21] (dotted lines), and AETC approach presented in [23] (dashed lines).

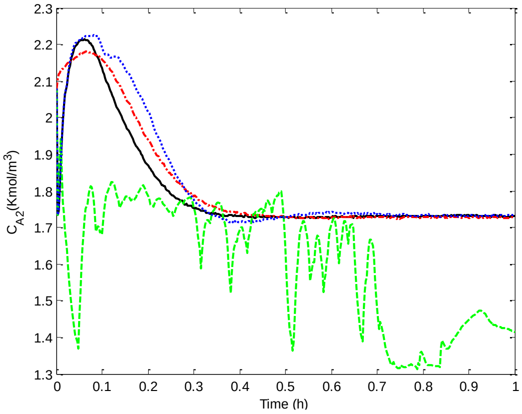

Fig. 4. The trajectories of state of the closed-loop system obtained via the suggested approach (solid lines) and resilient event-triggered output feedback control [32] (dashed-dotted lines), AETC approach presented in [21] (dotted lines), and AETC approach presented in [23] (dashed lines).

To show the efficiency of the proposed consensus control method for microgrids, this section uses an MG system model presented in [33] to control current sharing and voltage regulation. Fig. 9 shows that the DGU i has a complete hierarchical control in communication with its neighbors. All information about system modeling is mentioned in [33] in detail. It should be noted that the proposed event-triggered consensus control method that can also consider time delay is replaced with the one presented in [33]. Fig. 10 shows the graphs belonging to the studied MG including 5 DGUs, and as shown in the very figure, the physical and communication graphs are directional and non-directional, respectively. Scaling factors for DGUs are defined as $I_1^s = 1, I_2^s = 4, I_3^s = 2, I_4^s = 4, I_5^s = 1$.

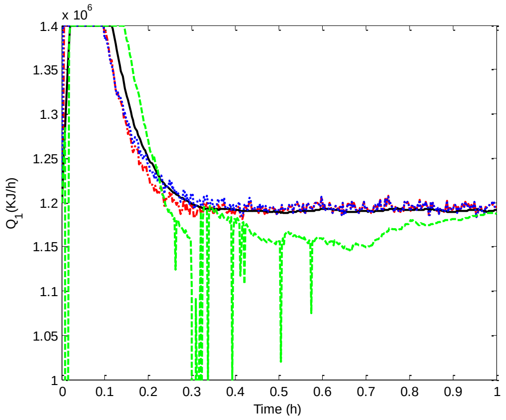

Fig. 5. The trajectories of input of the closed-loop system obtained via the suggested approach (solid lines) and resilient event-triggered output feedback control [32] (dashed-dotted lines), AETC approach presented in [21] (dotted lines), and AETC approach presented in [23] (dashed lines).

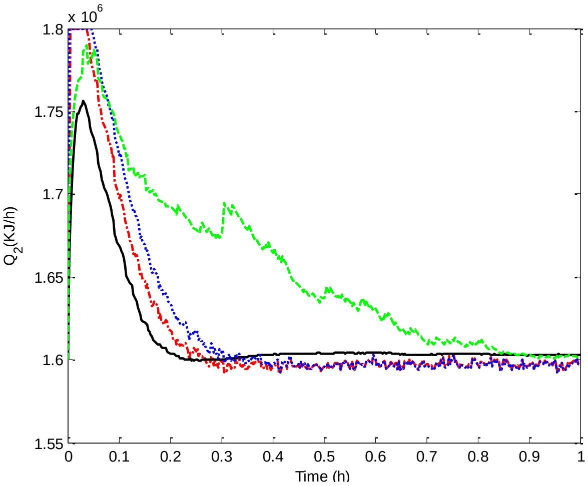

Fig. 6. The trajectories of input of the closed-loop system obtained via the suggested approach (solid lines) and resilient event-triggered output feedback control [32] (dashed-dotted lines), AETC approach presented in [21] (dotted lines), and AETC approach presented in [23] (dashed lines).

The reference voltage among the DGUs is set to $\bar{V}_{ref} = [40,50,48,42,46]^T$. The piece-wise constant load currents of DGUs numbered from 1 to 5 are considered as shown in Fig. 11. The electrical parameters belonging to DGs and primary control gains are given in [34] while sampling periods and secondary voltage control gains are stated in [33]. Fig. 12 depicts the voltage regulation for PCCs and current sharing calculated using the proposed event-triggered consensus control method. According to the results, It can be seen that the data transfer rate of DGs is higher in the proposed method than in the one introduced in [33].

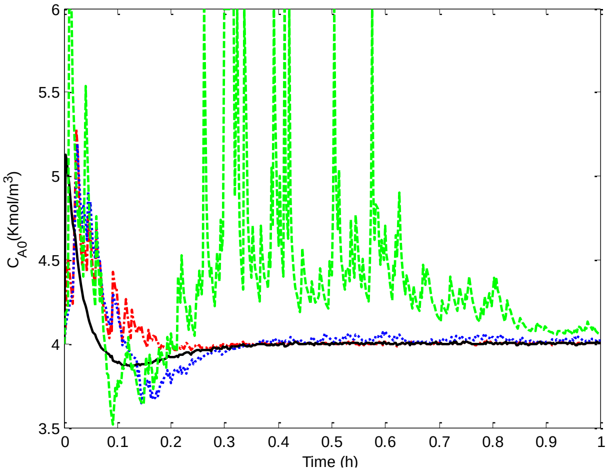

Fig. 7. The trajectories of input of the closed-loop system obtained via the suggested approach (solid lines) and resilient event-triggered output feedback control [32] (dashed-dotted lines), AETC approach presented in [21] (dotted lines), and AETC approach presented in [23] (dashed lines).

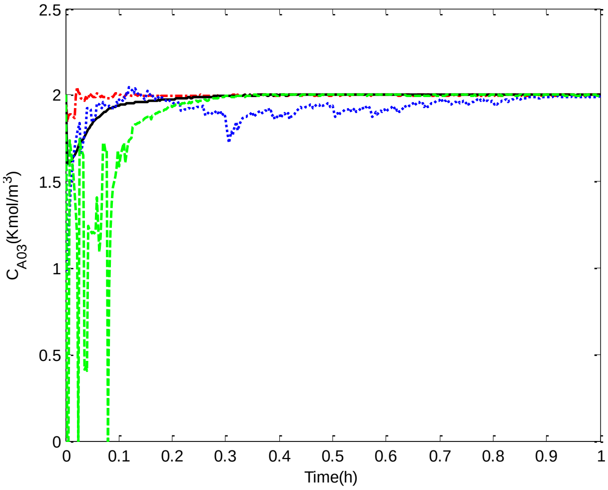

Fig. 8. The trajectories of input of the closed-loop system obtained via the suggested approach (solid lines) and resilient event-triggered output feedback control [32] (dashed-dotted lines), AETC approach presented in [21] (dotted lines), and AETC approach presented in [23] (dashed lines).

V. CONCLUSIONS

In this paper, the consensus problem of network-based heterogeneous multi-agent systems is evaluated by proposing an AETC algorithm. So, by considering the state information of agent *i* and other agents, an efficient AETC strategy is proposed to save the communication energy and reduce the frequency of data transmission, which are the main advantages of the proposed AETC approach. Moreover, the event-triggered time interval is considered a special delay and compensated by the predictive method. The optimal control is, furthermore, employed to design the PD-like predictive coordination controller. The condition for ensuring stability and consensus has been given. Finally, the developed method is applied successfully for the control of a network-based interconnected system with considering time delay.

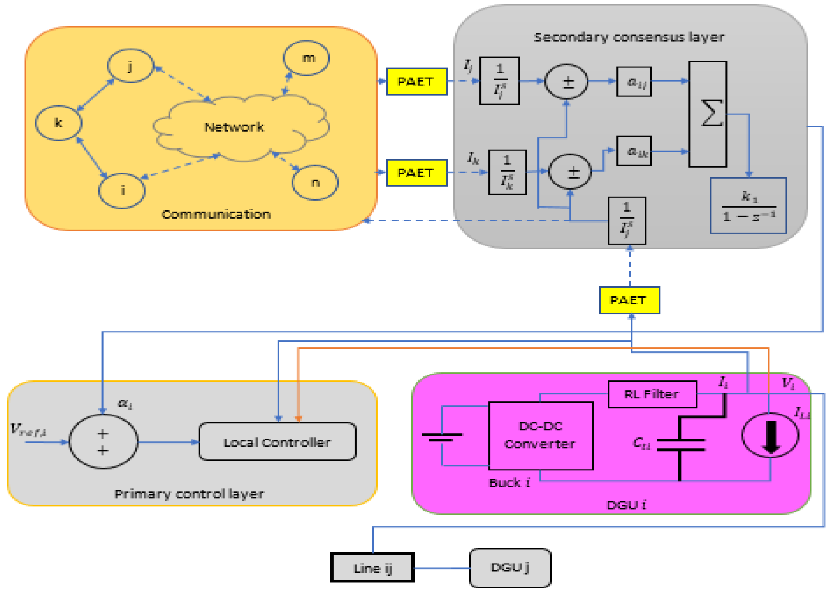

Fig. 9. The i_{th} DGU having complete hierarchical control in communication with its neighbors.

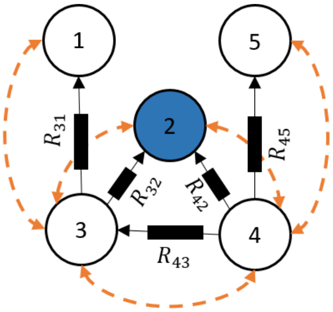

Fig. 10. Physical and communication graphs of a DC microgrid composed of 5 DGUs.

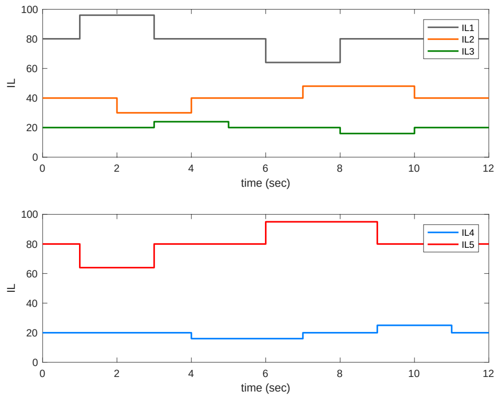

Fig. 11. The local load currents of the DGUs 1-5.

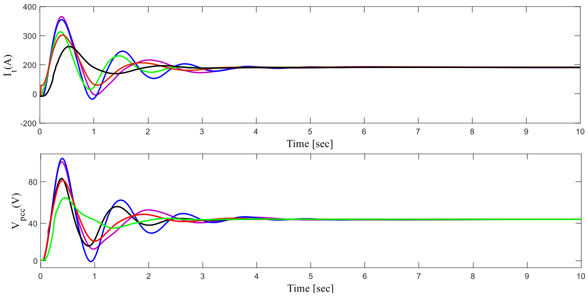

Fig. 12. The voltage regulation, current sharing, and average PCCs voltage of DGUs.

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