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Abstract—This paper investigates the fuzzy model predictive control synthesis of networked controlled power buffer for dynamic stabilization of a DC microgrid (MG). The proposed is based on Takagi-Sugeno (TS) fuzzy model and model predictive scheme to mitigate the network-induced delays from the sensor-to-controller and controller-to-actuator links. By employing the so-called time-stamp technique and network delay compensator (NDC), the delays are computed and compensated, which improves the effectiveness and robustness of the proposed controller. Due to the usage of two NDCs, the presented approach is robust against the network delays and results in small computational burden. Therefore, it can widely be employed on large distributed power systems. To show the merits of the proposed approach, it is applied to a DC MG that feeds one constant power load (CPL). Results show the simplicity of designing the controller and better robustness against the network's delays compared to the state-of-the-art methods. Additionally, hardware-in-the-loop (HiL) simulations are presented to prove the practical applicability of the proposed controller.

Index Terms—DC microgrid, constant power load, Takagi-Sugeno fuzzy model, model predictive controller, random network delay, hardware-in-the-loop (HiL).

I. INTRODUCTION

The advantages of the DC microgrid (MG), such as high efficiency and robustness, simple control, and natural interface for distributed generation (DG) as well as for electronic loads have made it become an interesting research area [1]. Among the topics, which have been studied in the DC MG, the controlling and stabilizing the DC MG with constant power loads (CPLs) has attracted a lot of attention, because the negative impedance property of the CPLs can make the overall system unstable [2], [3]. In order to alleviate undesired effects of the CPLs in such systems, several active nonlinear methods are proposed by modifying the control loop of injecting power, source converter, or load converter, including backstepping controller [4], [5], sliding mode controller [6], Takagi-Sugeno (TS) fuzzy-based robust controller [7] and model predictive control [8]. It should be noted that this study focuses on controlling the power buffer in the DC MG among

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other possible active methods. However, by increasing the number of CPLs, a point-to-point [9] communication from each CPL to the power buffer is not economical. Therefore, it may be preferred to control a large distributed DC MGs through a communication network. Recent advances on 5G networks with ultra high reliability and low latency [10] bring a proper platform to transfer data of the CPLs and storage system to the control center and the power buffer based on networked control system (NCS) topologies.

The NCSs comprise the controllers, sensors, and actuators that are spatially distributed and linked through a communication network [9], [11], [12]. The NCS scheme reduces system wiring and cost, improves data sharing and eases system diagnosis and maintenance [13]. Meanwhile, time delay, packet dropout, sampling, quantization, and bandwidth limitation are the major difficulties of an NCS, which make it more complicated than the traditional control system [14]. Therefore, the existing control approaches [4], [5], [7] are not applicable for a networked DC MGs with CPLs. Generally, one of the issues of the NCS is the so-called networked-induced delays which can be constant or time varying characteristics with random or deterministic characteristics [11]. In recent years, several control methods dealing with the networked induced delays are proposed. In [13], [15], networked infinite-horizon predictive controllers for linear systems with networked induced delays are proposed. By employing the Markovian jump theory in [13] and switched system concept in [15], the predictive controller gains are designed online via a linear matrix inequality (LMI) approach. However, based on these approaches, only linear systems can be stabilized. In [12], the network control of a class of nonlinear single-input-single-output (SISO) systems is considered. However, it is assumed that the nonlinear system is globally Lipchitz with respect to the control input; also in [16], an adaptive approach for networked nonlinear SISO systems with strict-feedback is proposed. However, the applicability of the approaches [12], [16] is limited, due to the fact that several nonlinear systems are not modeled by the representation given in [12], [16]. In [17], a predictive control approach for nonlinear systems with delay and data dropout is presented. However, it is assumed that the delay and data dropout has a pre-given stochastic characteristic and the input-to-state-practically-stable (ISpS) stability is developed to assure the closed-loop stability and boundedness of error of the system output. However, this approach has a high computational burden due to the usage of nonlinear

optimization solvers. Among the high consuming nonlinear model predictive methods, the combination of Takagi-Sugeno (TS) fuzzy model with MPC can provide a good compromise between the low computational burden and high performance [18]–[20]. In [21], an observer-based MPC for networked TS fuzzy systems subjected to data dropouts is studied. To assure the closed-loop stability, the data dropout is formulated by the Bernoulli stochastic distribution. Although the stability is assured offline, the time of the dropout is not employed in the controller design which degrades the performance. In [22], a predictive controller for time-delayed TS fuzzy systems is proposed through the LMI techniques. By considering a bounded disturbance, the input-to-state (ISS) stability scheme is considered to design the predictive controller. However, in [21], [22], the problem of network induced time delay is left behind.

In this letter, a systematic approach to design a networked controller for stabilizing power buffer in DC MGs with CPLs is proposed. The proposed approach employs the TS fuzzy model and model predictive controller (MPC) scheme to design the injecting current of the power buffer to stabilize the system. It is assumed that the links sensor-to-controller (STC) and controller-to-actuator (CTA) have random delays. By employing two network delay compensators (NDCs), the delays are evaluated and a novel MPC scheme is proposed to design the desired value of the injecting current. The proposed controller is robust against the random variables with any probability density function and has a low computational burden which makes the presented approach more applicable for practical implementations. The proposed approach has the following main advantages over the existing results: I) In this paper, a communication link for MGs with CPLs is considered. Meanwhile, the existing results only assumed a point-to-point communication link for DC MGs with CPLs [4], [5], [7]. This approach is not economical and even practical for MGs with a high number of CPLs. II) Comparing with the conventional networked predictive methods [12], [16], [17], this paper utilizes a Takagi-Sugeno (TS) fuzzy representation and merge it with a linear model predictive controller (MPC) scheme to provide a novel nonlinear fuzzy MPC that benefits a high performance in controlling nonlinear systems as well as low online computational burden. III) Comparing with the existing TS fuzzy model predictive approaches [18], [19], the proposed approach can compensate the random network delays with any stochastic characteristics. This improvement is achieved by proposing two network delay compensations (NDCs) and a novel formulation of the model predictive controller. Finally, hardware-in-the-loop (HiL) real-time simulation and experimental results illustrate the settling time reduction of the proposed approach compared to the state-of-the-art methods.

II. DC MICROGRID DYNAMICS

The schematic and circuit diagram of a DC MG comprising several constant power loads (CPLs) are shown in Fig. 1.
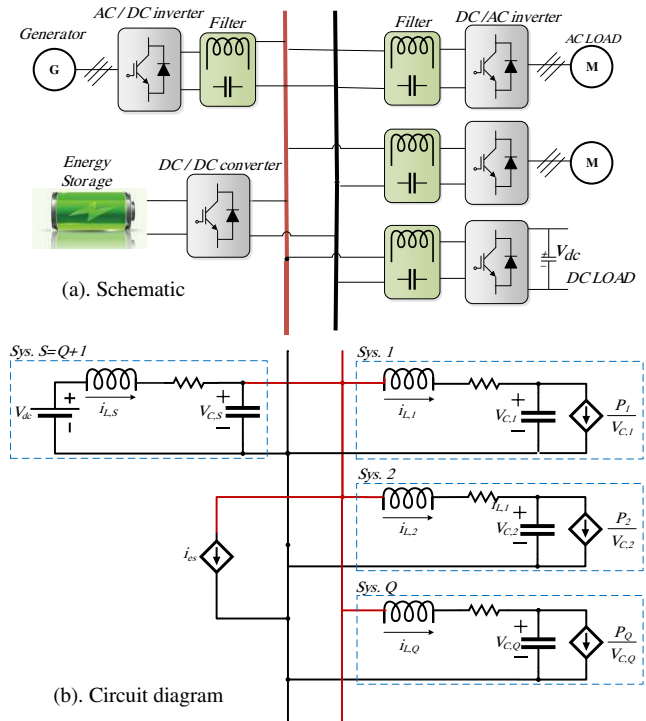

(a). Schematic

(b). Circuit diagram

Fig. 1. A detailed and simplified version of DC MG with Q CPLs used in more electric aircraft, navy ships, automotive, etc.

As it is evident from Fig. 1, we can decouple it into $Q + 1$ subsystems: Q CPLs and one energy storage system (ESS). The CPLs are of the form

$$\dot{x}_j = A_j x_j + d_j h_j + A_{js} x_s \qquad (1)$$

for $j = \{1,2,\dots,Q\}$ and $s = Q + 1$ where $x_j = \begin{bmatrix} i_{L,j} & v_{C,j} \end{bmatrix}^T$, $i_{L,j}$ and $c_{V,j}$ are the current of inductor and the voltage of the capacitor, respectively, in j-th CPL, and

$$A_j = \begin{bmatrix} -\dfrac{r_{L,j}}{L_j} & -\dfrac{1}{L_j} \\ \dfrac{1}{C_j} & 0 \end{bmatrix}, \quad d_j = \begin{bmatrix} 0 \\ \dfrac{P_j}{C_j} \end{bmatrix}, \quad A_{js} = \begin{bmatrix} 0 & \dfrac{1}{L_j} \\ 0 & 0 \end{bmatrix}, \qquad (2)$$

$$h_j = \frac{\tilde{v}_{C,j}}{v_{C0,j}\left(\tilde{v}_{C,j} + v_{C0,j}\right)}$$

It is assumed that the CPL is ideal and the value of the power is constant. The source subsystem can be written as

$$\dot{x}_s = A_s x_s + b_s V_{dc} + b_e i_{es} + \Sigma_{j=1}^{Q} A_{cn} x_j \qquad (3)$$

where $x_s = \begin{bmatrix} i_{L,s} & v_{C,s} \end{bmatrix}^T$, $i_{L,s}$ and $v_{C,s}$ are the current of inductor and the voltage of the capacitor, respectively, in the ESS, and

$$A_s = \begin{bmatrix} -\dfrac{r_s}{L_s} & -\dfrac{1}{L_s} \\ \dfrac{1}{C_s} & 0 \end{bmatrix}, b_s = \begin{bmatrix} \dfrac{1}{L_s} \\ 0 \end{bmatrix}, A_{cn} = \begin{bmatrix} 0 & 0 \\ \dfrac{-1}{C_s} & 0 \end{bmatrix}, \qquad (4)$$

$$b_{es} = \begin{bmatrix} 0 \\ -\dfrac{1}{C_s} \end{bmatrix}$$

Assuming a coordinated change near the operating point and letting the energy storage current i_{es} be the control input, we can rewrite the overall DC MG in the form [7]:

$$\dot{\tilde{X}} = \overline{A}\tilde{X} + \overline{D}h + \overline{B_{es}}\tilde{i}_{es} + \overline{B_s}\tilde{V}_{dc} \qquad (5)$$

where $\tilde{X} = \begin{bmatrix} x_1^T & x_2^T & \dots & x_Q^T & x_s \end{bmatrix}^T$, $h = \begin{bmatrix} h_1, \dots, h_Q \end{bmatrix}^T$, $\tilde{i}_{es}$ and $\tilde{V}_{dc}$ are the control input and voltage of the source in the new coordinate, respectively, and

$$\overline{A} = \begin{bmatrix} A_1 & 0 & \dots & 0 & A_{1s} \\ 0 & A_2 & \cdots & 0 & A_{2s} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & A_Q & A_{Qs} \\ A_{cn} & A_{cn} & \cdots & A_{cn} & A_s \end{bmatrix}, \overline{B_{es}} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ b_{es} \end{bmatrix}, \overline{B_s} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ b_s \end{bmatrix}$$

$$\overline{D} = \begin{bmatrix} d_1 & 0 & \dots & 0 \\ 0 & d_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & d_Q \\ 0 & 0 & \cdots & 0 \end{bmatrix} \qquad (6)$$

As it can be seen in (5) and (6), the overall MG system comprises of Q nonlinear terms (i.e. h_j). In order to derive the TS fuzzy model, the so-called sector nonlinearity approach is employed to exactly represent each of the nonlinearities by an equivalent TS model. Based on [7], the j-th CPL is locally stable in the region $R_{j,\tilde{x}} = \{\tilde{x} \mid -w_{1,j} \le \tilde{i}_{L,j} \le w_{1,j} \ \& \ -w_{2,j} \le \tilde{v}_{C,j} \le w_{2,j}\}$, where $w_{1,j}$ and $w_{2,j}$ are positive scalars, which can be obtained based on the LMI techniques [7]. Consequently, the equivalent TS fuzzy model of (5) for the regions $R_{\tilde{x},j}$ for $j = 1, \dots, Q$ can be obtained.

III. TS-BASED NETWORK CONTROL SYSTEMS

Complex and large distributed DC MGs can be connected over Ethernet and/or wireless, as illustrated in Fig 2. In the 5G scenario, packet-based messages are exchanged at ms time-scale, which makes dynamic stabilization possible [10]. However, because of the high data exchange over the communication channel, random packet dropouts and network-induced delays are likely to occur.

In this letter, a novel TS-based networked predictive control (NPC) is presented as shown in Fig. 3. In order to compensate the network transmission delay, network delay compensators (NDCs) in the channels from the controller-to-actuator (CTA) and the sensor-to-controller (STC) are placed. Additionally, since the network's delays τ_t and d_t are random, data may be received non-sequentially to the NDCs. Thus, the NDCs select the latest time-stamped data from all receiving data at a specific time.
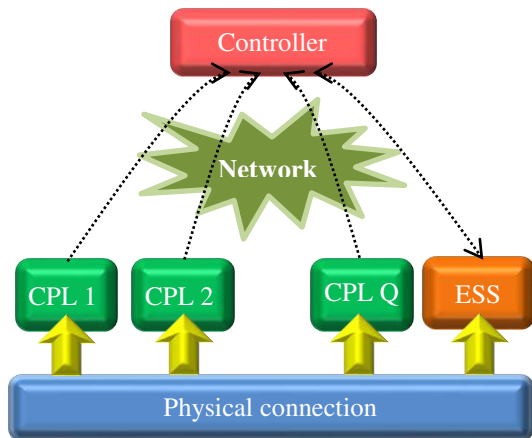

Fig. 2. Networked DC MGs with CPLs and ESS.

For example, at the time k with two receiving times-stamped k_1 and k_2 packets ($k_1 > k_2$), the NDCs keep the time-stamped k_1 packet and calculate the network delay as $k - k_1 \ge 0$.

Based on the following assumptions, a novel networked controller will be proposed.

Assumption 1: The data transmitted through a network are time-stamped.

Assumption 2: The network delay τ_t in the forward channel from controller to actuator (CTA) is bounded by τ.
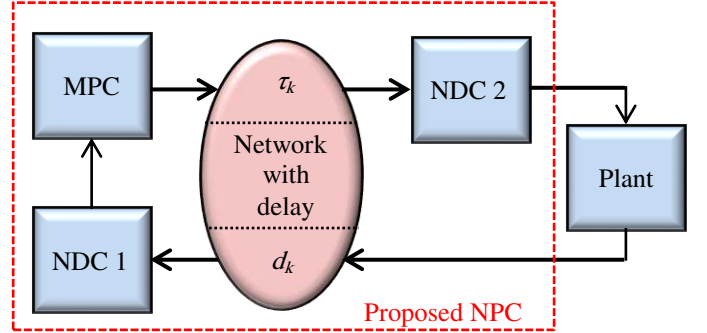

Fig. 3. The proposed network predictive control scheme with two NDCs.

Since model predictive scheme uses a discrete-time system to predict the future behavior, consider the following discrete-time TS fuzzy system

$$x_{k+1} = \sum_{i=1}^{r} h_i A_i x_k + \sum_{i=1}^{r} h_i B_i u_k + \sum_{i=1}^{r} h_i E_i \qquad (7)$$
$$= A_h x_k + B_h u_k + E_h$$

Based on the information available at the controller side (i.e. the system states and the STC's delay d_k computed by the NDC 1) and the model (7), the predictions up to the $k + \tau$ can be calculated as

$$\begin{bmatrix} \hat{x}_{k-d_k+1|k-d_k} \\ \hat{x}_{k-d_k+2|k-d_k} \\ \vdots \\ \hat{x}_{k|k-d_k} \\ \vdots \\ \hat{x}_{k+\tau|k-d_k} \end{bmatrix} = \begin{bmatrix} A_h \\ A_h^2 \\ \vdots \\ A_h^{d_k} \\ \vdots \\ A_h^{d_k+\tau} \end{bmatrix} x_{k-d_k} + \begin{bmatrix} E_h \\ (I+A_h)E_h \\ \vdots \\ \sum_{i=0}^{d_k-1} A_h^i E_h \\ \vdots \\ \sum_{i=0}^{d_k+\tau-1} A_h^i E_h \end{bmatrix}$$

$$+ \begin{bmatrix} B_h & 0 & \dots & 0 \\ A_h B_h & B_h & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A_h^{d_k+\tau-1}B_h & A_h^{d_k+\tau-2}B_h & \dots & A_h^{\tau-2}B_h \end{bmatrix} \begin{bmatrix} u_{k-d_k} \\ u_{k-d_k+1} \\ \vdots \\ u_{k-1} \end{bmatrix}$$

$$+ \begin{bmatrix} 0 & \dots & 0 \\ B_h & \dots & 0 \\ \vdots & \ddots & \vdots \\ A_h^{\tau-1}B_h & \dots & B_h \end{bmatrix} \begin{bmatrix} u_k \\ u_{k+1} \\ \vdots \\ u_{k+\tau} \end{bmatrix} \qquad (8)$$

Since there is no control on the past states $\hat{x}_{k-d_k+1|k-d_k}, \dots, \hat{x}_{k-1|k-d_k}$, these values are not changeable and one can omit them in the MPC formulation. By removing the corresponding rows of (8), it can be expressed in a vector form

$$X = \Psi + \Theta U \qquad (9)$$

where

$$X = \begin{bmatrix} \hat{x}_{k|k-d_k} \\ \hat{x}_{k+1|k-d_k} \\ \vdots \\ \hat{x}_{k+\tau|k-d_k} \end{bmatrix}, U = \begin{bmatrix} u_k \\ u_{k+1} \\ \vdots \\ u_{k+\tau} \end{bmatrix}, \Theta = \begin{bmatrix} B_h & \dots & 0 \\ A_h B_h & \dots & 0 \\ \vdots & \ddots & \vdots \\ A_h^{\tau-1} B_h & \dots & B_h \end{bmatrix}$$

$$\Psi = \begin{bmatrix} A_h \\ A_h^2 \\ \vdots \\ A_h^{d_k+\tau} \end{bmatrix} x_{k-d_k} + \begin{bmatrix} \sum_{i=0}^{d_k-1} A_h^i E_h \\ \sum_{i=0}^{d_k} A_h^i E_h \\ \vdots \\ \sum_{i=0}^{d_k+\tau-1} A_h^i E_h \end{bmatrix}$$

$$+ \begin{bmatrix} A_h^{d_k-1} B_h & A_h^{d_k-2} B_h & \dots & B_h \\ A_h^{d_k} B_h & A_h^{d_k-1} B_h & \dots & A_h B_h \\ \vdots & \vdots & \ddots & \vdots \\ A_h^{d_k+\tau-1} B_h & A_h^{d_k+\tau-2} B_h & \dots & A_h^{\tau} B_h \end{bmatrix} \begin{bmatrix} u_{k-d_k} \\ u_{k-d_k+1} \\ \vdots \\ u_{k-1} \end{bmatrix}$$

Note that the Ψ comprises all the available information belonging to the past and U comprises the unknown future control inputs, which should be designed by the MPC techniques. To perform this, consider the following cost function [17]:

$$J = \sum_{j=0}^{\tau} \delta_j [\hat{x}_{k+j|k-d_k} - w_{k+j}]^2 + \sum_{j=0}^{\tau} \lambda_j u_{k+j}^2 \qquad (10)$$

where w_{k+j} is the function of future reference, and the coefficients δ_j and λ_j determine the weights of the future behavior and control input energy. Rewriting the cost function (10) in a vector representation, yields

$$J = \Delta(Y - W)^T (Y - W) + \Lambda U^T U \qquad (11)$$

where $\Delta = \text{diag}\{\delta_0, \delta_1, \dots \delta_\tau\}$ and $\Lambda = \text{diag}\{\lambda_0, \lambda_1, \dots, \lambda_\tau\}$ with diag$\{.\}$ stands for a diagonal matrix, and $W = [w_k \quad w_{k+2} \quad \dots \quad w_{k+\tau}]^T$. By substituting (9) into (11), one has

$$J = U^T H U + K U + U^T K^T + G \qquad (12)$$

where

$$H = \Theta^T \Theta + \Lambda \geq 0, K = (\Psi - W)^T \Delta \Theta, G = (\Psi - W)^T \Delta (\Psi - W)$$

The optimization problem is to minimize J with respect to U. This quadratic problem has the following analytic solution. By letting the derivative of (12) with respect to the vector U to be zero, one has

$$U = (\Theta^T \Theta + \Lambda)^{-1} \Theta^T \Delta (\Psi - W) \qquad (13)$$

Remark 1 (design procedure of the proposed controller): Initially, the block NDC 1 picks the latest time-stamped data from the sensor and measures the STC's delay d_k. Based on the received x_{k-d_k} and the upper bound of CTA's delay τ, the matrices Ψ and Θ, defined in (9), are computed. Therefore, the sequence of future control inputs U is obtained by (13). The time-stamped packet of U is transferred to the actuator through the network. Then, the NDC 2 chooses the latest time-stamped data from the controller; evaluates the CTA's delay τ_k; and applies the control law $u_{k+\tau_k}$ to the system. If the NDCs 1 and/or 2 do not receive any data for some times, they use the latest data and

increase the delays d_k and/or τ_k by one. Fig. 4 shows the schematic of the proposed controller.

Remark 2 (degrees of freedom of the proposed controller): The proposed optimal controller design is on the basis of minimization of the cost function (10). The scalars δ_j and λ_j in (10) are the design parameters which are selected by the designer. Generally, these parameters affect the transient performance or the amplitude and energy consumption of the control input. The high value of δ_j leads to better transient performance; meanwhile, the higher λ_j corresponds less injecting current. These parameters provide a degree of freedom in designing the optimal value of the injecting current so that the closed-loop system can have a better transient performance or consume less energy.

Remark 3 (merits of the proposed networked control scheme):

I) In the proposed approach, the NDC 2 is added for the first time. Therefore, the delay of STC is exactly available. Thereby, the proposed NPC is established based on the exact value of d_t, and any assumption on the upper bound of STC's delay is not needed in this brief; and, the only assumption on the network delays is the known upper bound of the CTA's delay. However, in [9], [13], [14], only one NDC at the CTA is placed. Consequently, Refs. [9], [13], [14] assumed that both STC and CTA delays are bounded by known limits; and Refs. [13], [23] model the delays as homogeneous Markov chains. These extra considerations confine the applicability of the [9], [13], [14], [23] in real processes.

II) Comparing with [9], [13], [14], [17], [23], the proposed control methodology by employing the values of random delays in the control design, reduces the computational time burden of the controller design; since, the dimensions of $\Psi \in \mathcal{R}^{(d_t+\tau)\times(d_t+\tau)}$ are dependent to d_t. However, the other control approaches consider the upper bound of STC's delay which undesirably increases the dimensions. As a consequence, the proposed approach can be implemented with a cheaper hardware.

IV. SIMULATION RESULTS

To investigate the robustness and fast transient performance of the proposed approach, it is tested on the MG with the parameters given in Table I and the results are compared with networked ISpS-MPC [17]. The schematic of the case study with the communication link is illustrated in Fig. 5. As it can be seen in Fig. 5, the states of the filters are transmitted to the MPC block through the communication link. First, the NDC 1 computes the STC delay d_k. Then, the MPC block uses the receiving values of the states and the d_k to compute the sequence of the control input and send it to the ESS unit via the communication link. At this stage, the NDC 2 computes the CTA delay τ_k and select the paper control input $\tilde{i}_{es}$ from the receiving control input sequence U. The values of the RLC Filters 1 and 2 are given in Table I.

In addition, in order to prove the performance and robustness of the suggested approach, the hardware-In-the Loop (HiL) simulation technique is applied. One of the advantages of the real-time HiL technique in comparison to the classical off-line simulations is that it can emulate delays

and errors. The layout of the HiL based on the RTS is depicted in Fig. 6. The structure of the HiL is shown in Fig. 6, which consists of 1) OPAL-RT as a real-time Simulator (RTS) which simulates the proposed controller depicted in Fig. 6; 2) a PC as the command station (programming host) in which the Matlab/Simulink based code that is executed on the OPAL-RT is generated; and 3) a router used as a connector for all the setup devices in the same sub-network. The OPAL-RT is also connected to a DK60 board [3] through Ethernet ports.
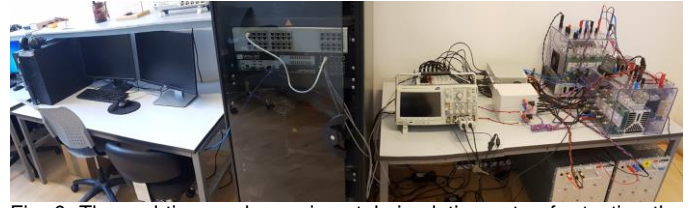

Fig. 6. The real-time and experimental simulation setup for testing the control approach.
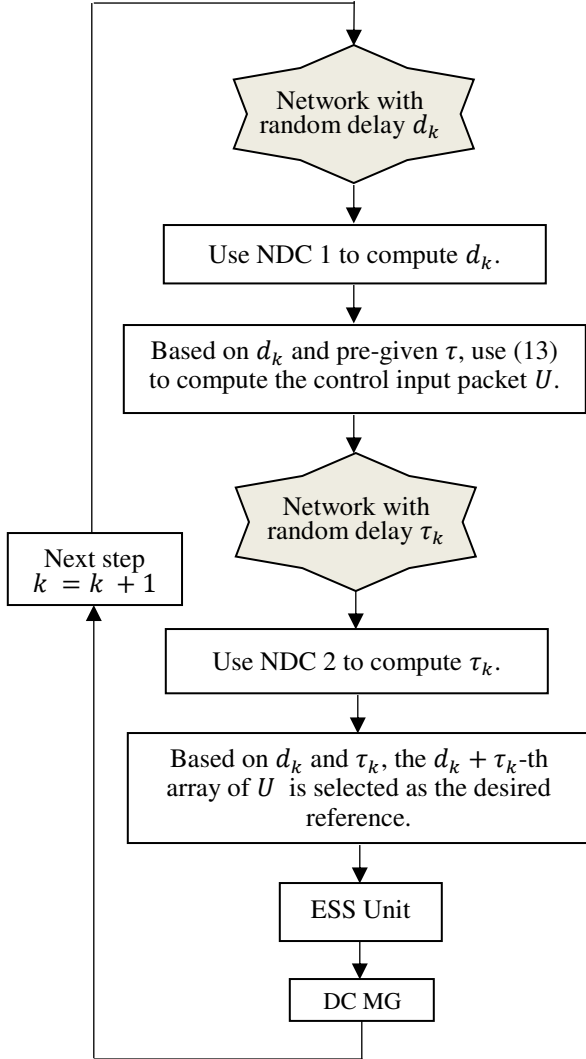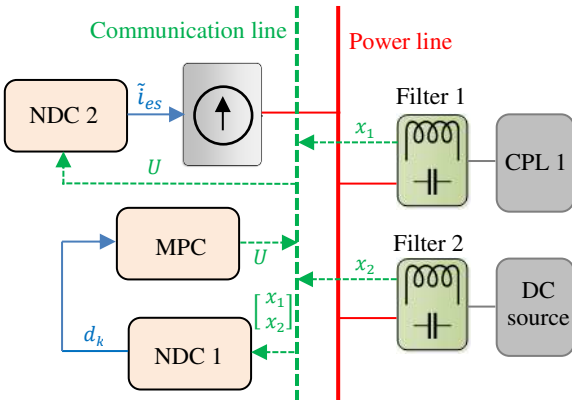
TABLE I
PARAMETERS FOR DC MG WITH ONE CPL

$r_1 = 1.1\ \Omega$	$v_{C0,1} = 196.64$	$C_s = 500\ \mu F$	$L_s = 39.5\ mH$
$C_1 = 500\ \mu F$	$\widetilde{w}_{2,1} = 130.4$	$V_{dc} = 200\ V$	$L_1 = 39.5\ mH$
$P_1 = 300\ W$	$r_s = 1.1\ \Omega$		

Without loss of generality, consider an MG with one CPL and one source [24]. Since $-\widetilde{w}_{2,1} \le \tilde{v}_{C,1} \le \widetilde{w}_{2,1}$, one has $U_{min} \le \frac{h_1}{\tilde{v}_{C,1}} \le U_{max}$ where the lower and upper bounds U_{min} and U_{max} are

$$U_{min} = \frac{1}{v_{C0,1}\left(\widetilde{w}_{2,1} + v_{C0,1}\right)}, U_{max} = \frac{1}{v_{C0,1}\left(-\widetilde{w}_{2,1} + v_{C0,1}\right)} \quad (14)$$

Based on the sector nonlinearity approach [25], the equivalent TS fuzzy model can be obtained as

$$\dot{\tilde{X}} = \Sigma_{i=1}^2 M_i\{A_i\tilde{X} + B_{es}\tilde{i}_{es} + B_s\tilde{V}_{dc}\} \quad (15)$$

where $M_1 = \frac{U_{max}\tilde{v}_{C,1} - h_1}{(U_{max} - U_{min})\tilde{v}_{C,1}}$; $M_2 = \frac{h_1 - U_{min}\tilde{v}_{C,1}}{(U_{max} - U_{min})\tilde{v}_{C,1}}$, and

$$A_1 = \begin{bmatrix} -\frac{r_1}{L_1} & -\frac{1}{L_1} & 0 & \frac{1}{L_1} \\ \frac{1}{C_1} & \frac{P_1}{C_1}U_{min} & 0 & 0 \\ 0 & 0 & -\frac{r_s}{L_s} & -\frac{1}{L_s} \\ -\frac{1}{C_s} & 0 & \frac{1}{C_s} & 0 \end{bmatrix}, B_{es} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -\frac{1}{C_s} \end{bmatrix},$$

$$A_2 = \begin{bmatrix} -\frac{r_1}{L_1} & -\frac{1}{L_1} & 0 & \frac{1}{L_1} \\ \frac{1}{C_1} & \frac{P_1}{C_1}U_{max} & 0 & 0 \\ 0 & 0 & -\frac{r_s}{L_s} & -\frac{1}{L_s} \\ -\frac{1}{C_s} & 0 & \frac{1}{C_s} & 0 \end{bmatrix}, B_s = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_s} \\ 0 \end{bmatrix}$$

$$(16)$$

Fig. 4: The schematic of the proposed controller.

Fig. 5: The schematic of the proposed controller.

To show the merits of the proposed approach, three scenarios are considered. In the two first cases, the proposed approach is compared with the robust linear [7] and ISpS-MPC [17] methods. Meanwhile, in the last scenario, a practical experiment is performed.

Scenario 1 (Ideal Communication Network with no delay): The goal of this scenario is to show the performance improvement of the proposed predictive controller over the existing conventional approaches. Since the robust linear controller [7] is developed for a point-to-point communication without any delay, in this scenario, the STC and CTA delays are set as zero to provide a fair comparison. However, the upper bound of the CTA delay is chosen as $\tau = 5$. This consideration can be regarded as the predication horizon for

the predictive controller. The simulation is carried out by choosing the initial conditions $\tilde{X} = [1.5\ \ 212\ \ 1.5\ \ 210]^T$. The reference values for the currents and voltages of the filters of the CPL and the DC source are selected as same as [7]. Fig. 6 illustrates the closed-loop current and voltages evolutions and the injecting current for the proposed approach and robust linear [7].
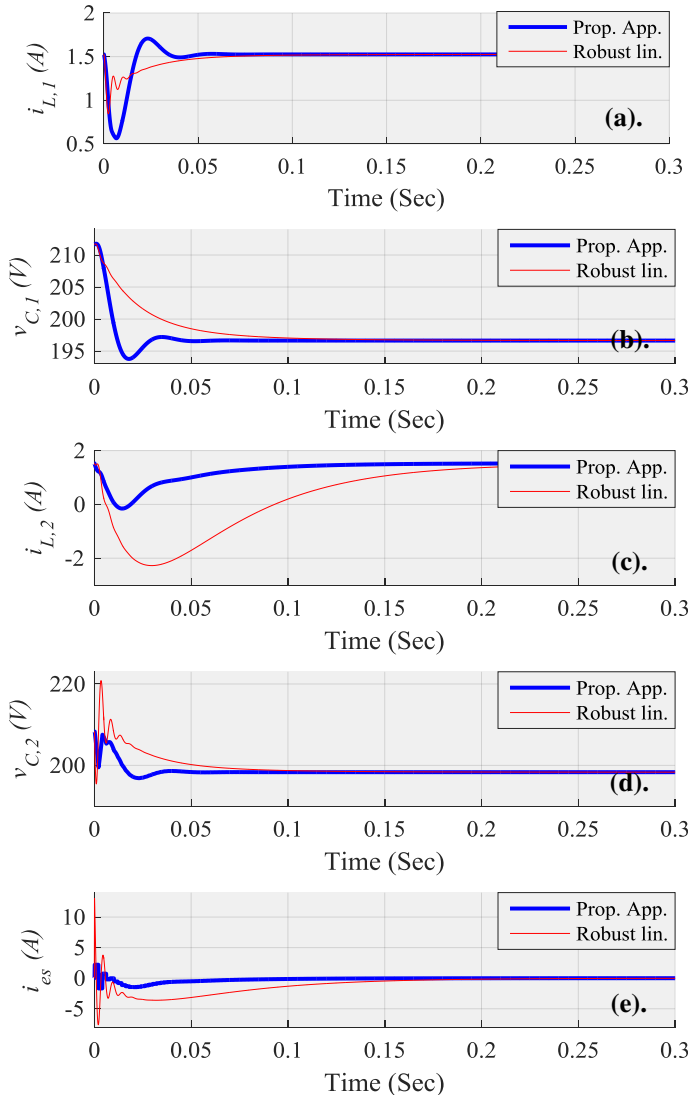

Fig 6. The DC MG's states and control input of scenario 1.

Fig. 6 reveals that proposed approach stabilizes the DC MG faster and with fewer oscillations than the robust linear [7] which shows the performance improvement of the proposed predictive method than the conventional techniques. Also, the amplitude of the injection current based on proposed approach is smaller than that of [7].

Scenario 2 (Non-ideal Communication network with random STC and CTA delays): In this scenario, the effectiveness of the proposed approach for networked DC MGs with random delays is investigated. The range of the STC and CTA random delays is selected as $d_k, \tau_k \in [0\ \ 20]\ ms$. Note that the conventional point-to-point approach [7] is not able to stabilize the DC MG through a non-ideal communication link with the given range of the delays.

Therefore, for comparison, another MPC technique called ISpS-MPC [17] is considered. The initial conditions $\tilde{X} = [0\ \ 15\ \ 0\ \ 10]^T$ are set as same as the scenario 1. Also, the current $\tilde{i}_{es}$ is saturated by lower and upper limits of ± 8.

Fig. 7 demonstrates the closed-loop voltage and current of the CPL and energy storage and the controlled current of the energy storage supply. Simulation results show that the proposed simple nonlinear approach effectively improves the transient performance of the DC MG. Fig. 6 reveals that the settling time of the closed-loop DC MG is reduced more than 3 times compared to the ISpS-MPC [17].
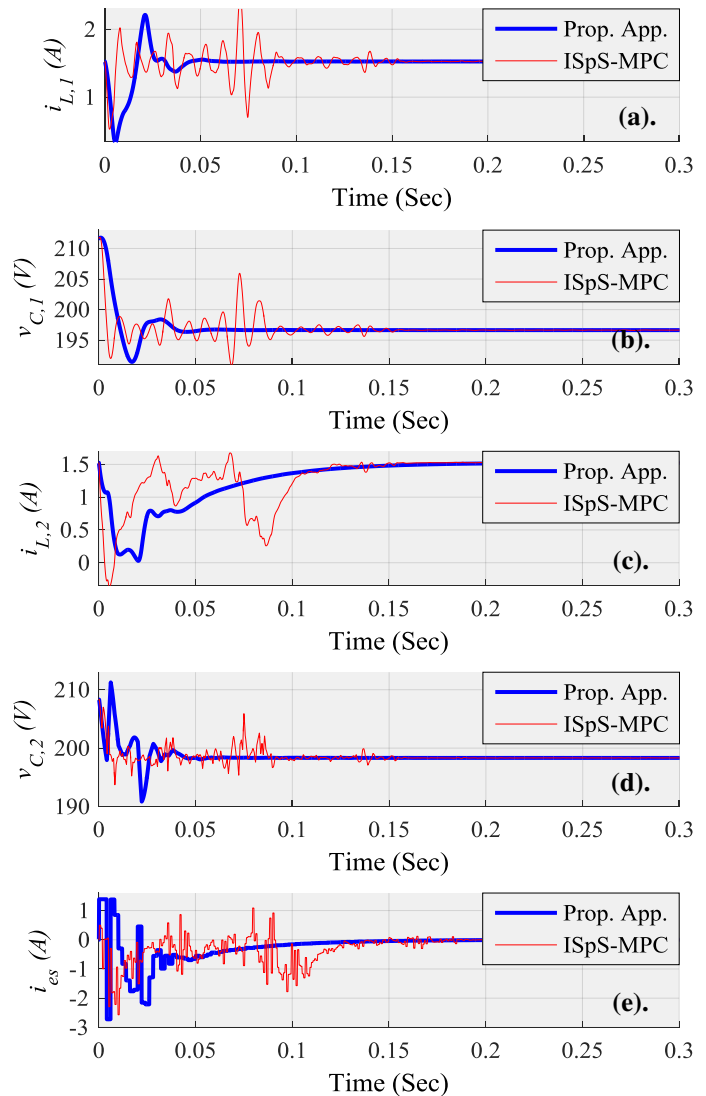

Fig 7. The DC MG's states and control input of scenario 2.

Fig. 7 illustrates that the proposed approach can better mitigate the networked induced-delays than the ISpS-MPC [17].

Scenario 3 (Experimental simulation): In this scenario, the proposed control strategy is tested experimentally on a test system given in Fig. 6. The control algorithm is implemented in the DSpace MicroLabBox with DS1202 PowerPC Dual-Core 2 GHz processor board and DS1302 I/O board. The range of the random delays is set as same as the scenario 2.

Also, the nominal values of the system parameters which are employed in the proposed controller are given in Table 1.

Fig. 8 shows the closed-loop states and control input. It is evident from Fig. 8 that the proposed predictive controller stabilizes the voltage of the DC MG (i.e. $v_{C,2}$) in about $0.15\ s$.
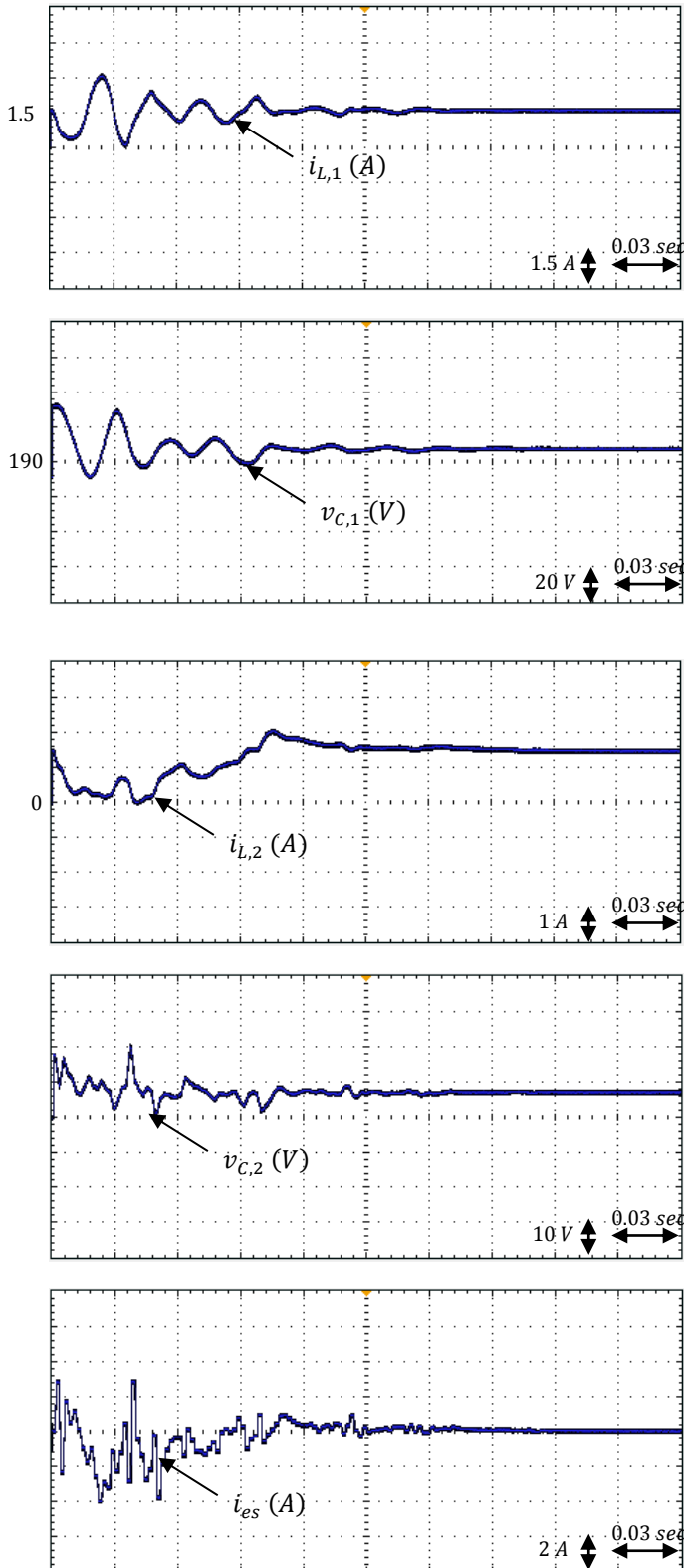

Fig 8: The DC MG's states and control input of scenario 3.

V. CONCLUSION

In this paper, a novel TS-based fuzzy MPC law for regulating the current of the energy storage unit connected with multiple CPLs in a networked DC MG is proposed. At each time instance, the NDCs evaluate the networks' delays and the proper control law is designed based on a predictive scheme. The proposed approach can be applied to nonlinear networked plants with any networked-induced delays with any probability density function (PDF). Hil real-time simulations verify the effectiveness and performance improvements of the proposed approach over the state-of-the-art controllers. For the future work, considering data loss in the network links and designing stabilizing controller with fewer sensors can be good research topics. It should be noted that considering the droop control problem for networked DC MGs with several ESSs is of great importance. Furthermore, it is suggested to study the effect of the varying CPLs on the system performance and provide a mechanism to estimate the power of CPLs to further improve the results of this paper.

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