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A Fuzzy Inference Model for Distributed Secondary Control of Islanded Microgrids

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Abstract— ***In this paper a fuzzy logic-based distributed secondary control is introduced for islanded microgrids. Inspired by techniques from cooperative control, the presented controllers use local information and neighbor communication to perform secondary control actions. Consensus protocols are used for regulating voltage and sharing the active and reactive power. To tune the communication weights used in the consensus-based distributed framework, a smart fuzzy logic-based method is presented. The presented method estimates the appropriate amount of communication weights according to the fuzzy states, and relation between inputs and outputs considering stability criteria. A microgrid with three sources is used to verify the effectiveness of the proposed contribution. MATLAB/SIMULINK® is used for modelling and simulation of the system.***

Keywords- Consensus protocol, distributed control, fuzzy logic, microgrid, secondary control.

I. INTRODUCTION

The trend of new electrical grids is becoming more and more distributed, and hence, energy generation units and consumption areas cannot separately be conceived. The new electrical grids are named smart grid (SG) which transfer electricity from the generation units to consumption areas by using digital technology for controlling appliances at consumers' homes to save energy, which will be reducing cost and increasing reliability. Hence, the expected energy system will have flexibility and intelligence. Microgrids (MGs) are becoming important concepts to integrate Distributed generation (DG) and energy-storage systems (ESS).

A hierarchical function is used in MGs to have a successful operation and addressing control requirements [1]. A decentralized approach based on primary control is adopted to improve frequency and voltage regulation [2]. The droop method, also called P-f and Q-V droops, has been applied to stabilize the network and obtaining good power sharing [3]. A virtual impedance loop is often added to the existing control loops, in order to improve the reactive power sharing in the presence of line impedance effect. In decentralized approaches, digital communication is not utilized, thus controllability of the whole system is not guaranteed [5].

Moreover, disadvantages of the primary control are its load-dependent frequency/voltage deviations, the poor performance of reactive sharing and not sufficient support of nonlinear loads. These problems lead to next level of hierarchy control named secondary control. Centralized secondary controller that located in the microgrid central controller is practiced to restore the frequency and voltage to their nominal values [1]-[3]. The centralized structure is confront of the MG paradigm of DG and autonomous management [4]. Distributed control structures have been introduced to overcome the weakness of the centralized and decentralized control methods. Distributed secondary control have been presented for control of MG to achieve system's less complexity [6], frequency synchronization and voltage regulation, secure active and reactive power sharing [7], and compensation of harmonics and unbalances [8]. These distributed control approaches are mostly based on normal averaging method [9] or consensus protocols [10]. Consensus-based distributed approaches have gained popularity recently, they guarantee a good performance with a sparse communication network [9]-[10]. However, the consensus protocol parameters, i.e., the communication weights, may affect the system stability thus, they need to be well tuned.

This paper introduces a distributed control framework including voltage, and reactive power sharing regulators. The control methodology regulates the voltage of the system and simultaneously manages the reactive power sharing among the DGs using consensus protocols. In the voltage regulator the consensus protocol are used to estimate the averaged voltage. The reactive power sharing regulator by comparing the local generation with its neighbors' shifts the droop coefficient to mitigate mismatching. A sparse communication network contains a connected graph has been used to link the source controllers in order to exchange the information. An intelligent method based on fuzzy logic (FL) is proposed to fine tune the consensus parameters. Fuzzy systems try to emulate cognitive processes of the brain with a rule base. In order to train the fuzzy logic processor, it is necessary to know the ranges and effects of each consensus parameters on frequency and voltage stability. Then, FL based on relation between inputs and output

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and information about the system stability would generate the best values for consensus parameters.

We categorized taken information to present an overall framework. This paper is organized as follows: Section II discuses about the concept of dynamic consensus protocol. The proposed cooperative control framework and the distributed secondary control is discussed in Section III. Section IV presents a fuzzy logic based dynamic consensus protocol. In Section V, results are given to show the feasibility of the proposed method. Finally, section VI concludes the paper.

II. REVIEW OF DYNAMIC CONSENSUS PROTOCOL

Consensus protocol has originally roots in the computer science [11]. Recently, this methodology is more and more used in multi-agent to facilitate the coordination among huge number of distributed agents, i.e., DGs in microgrids [12]. The main aim of this method is allowing a set of agents (DGs) in a MG to agree on a quantity of interest by sharing data through cyber network. In a MG, these protocols can exchange the information and coordinate them among DGs, consumers and storage systems. An adjacent matrix is defined to show the underlying communication structure which plays a significant role on convergence and dynamic analysis.

Fig. 1 depicts a typical directed communication graph for a multi-agent system. Consider a multi-agent system that $V = (v_1, v_2, \dots, v_n)$ *a set of nodes,* $\varepsilon \subseteq \{(v_j, v_i) | i, j \in N\}$ *a set of edges,* $x_i \in R$ *is value of each node* v_i*, and* $G_i = (G, x)$ *which* $x = (x_1, \dots, x_n)^T$ *as a network value and* G *is information flow. In the dynamic consensus two ends of edge makes a loop. The value of nodes could include physical quantity, e.g., output impedance or line impedance. The adjacent matrix A includes the communication weights,* a_{ij} *. Once agent i receives direct information from agent j,* $a_{ij} = 1$ *, otherwise* $a_{ij} = 1$ *.*

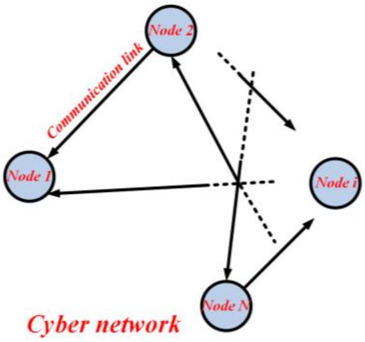


Fig. 1. The graphical scheme of a cyber-physical system.

III. DISTRIBUTED SECONDARY CONTROL

A. Cooperative Control Structure

Fig. 2 presents a control methodology for each DG consisting of two modules; voltage regulator, and reactive power regulator. While the reactive power regulator manages the reactive power sharing between the DGs by adding a correction term to the droop control loop, the voltage regulator holds the averaged voltage at the rated value.

To apply the consensus protocol a communication graph with an adjacency matrix A is needed. An example of adjacency matrix is shown for three agents as follows,

$$A = \begin{pmatrix} 0 & a_{12} & 0 \\ a_{21} & 0 & a_{23} \\ 0 & a_{32} & 0 \end{pmatrix}. \tag{1}$$

The information, i.e., voltage and reactive power are shared through the communication network by a vector as

$$\psi_j = \left[\overline{E_j}, {Q_j}/{Q_{j\max}} \right]. \tag{2}$$

where $\overline{E_j}$ *is voltage estimation of agent j,* Q_j *and* Q_{jmax} *are the supplied reactive power, and rated reactive power, respectively.*

B. Voltage Regulation and Reactive Power Sharing

As shown in Fig. 2, the secondary controller at each sources carries two modules. A voltage correction term adjust the voltage set point for each nodes, i.e., $E_{DGi} = E + \delta E^1_{DGi} + \delta E^2_{DGi}$ *, where* E *is the reference voltage of the each node, and* δE^1_{DGi} *, is the correction terms produced by the voltage regulator, and reactive power regulator, respectively. To find the term* δE^1_{DGk}*, the voltage regulator uses dynamic consensus to estimate the averaged voltage at node i. It updates the averaged amplitude without measuring the other nodes directly as*

$$\overline{E_i}(t) = \int \left(\sum_{j=1}^{N} b a_{ij} \{ \overline{E_j}(\tau) - \overline{E_i}(\tau) \} \right) d\tau + E_i(t). \tag{3}$$

where a_{ij} *is communication weight between agent i and j, b is a gain related to the consensus protocol,* E_i *is the voltage amplitude at node i,* $\overline{E_j}$ *is the estimated averaged voltage received from direct neighbour, node j . As shown in (3), the consensus protocol uses local voltages to estimate the voltage at each node i. By using a connected communication graph, the variation of* $\overline{E_i}$ *effects affects all other voltage estimators. The line impedance causes the voltage output of busses not equal with the others. Once* $\overline{E_i}(t)$ *is generated by (3), it is passed through a PI controller to produce the correction term,* δE^1_{DGi} *as*

$$\delta E^1_{DGi} = k_{pv}\left(E_{ref} - \overline{E_i}(t)\right) + k_{iv} \int \left(E_{ref} - \overline{E_i}(t)\right) d\tau. \tag{4}$$

The second term, δE^2_{DGi}*, is produced by the reactive power regulator. This term tries to manage the reactive power sharing between agents. The information,* Q_j / Q_{jmax} *, are received from all the neighbors, compared with the local information,* Q_i / Q_{imax}*, and then fed to a PI controller as following:*

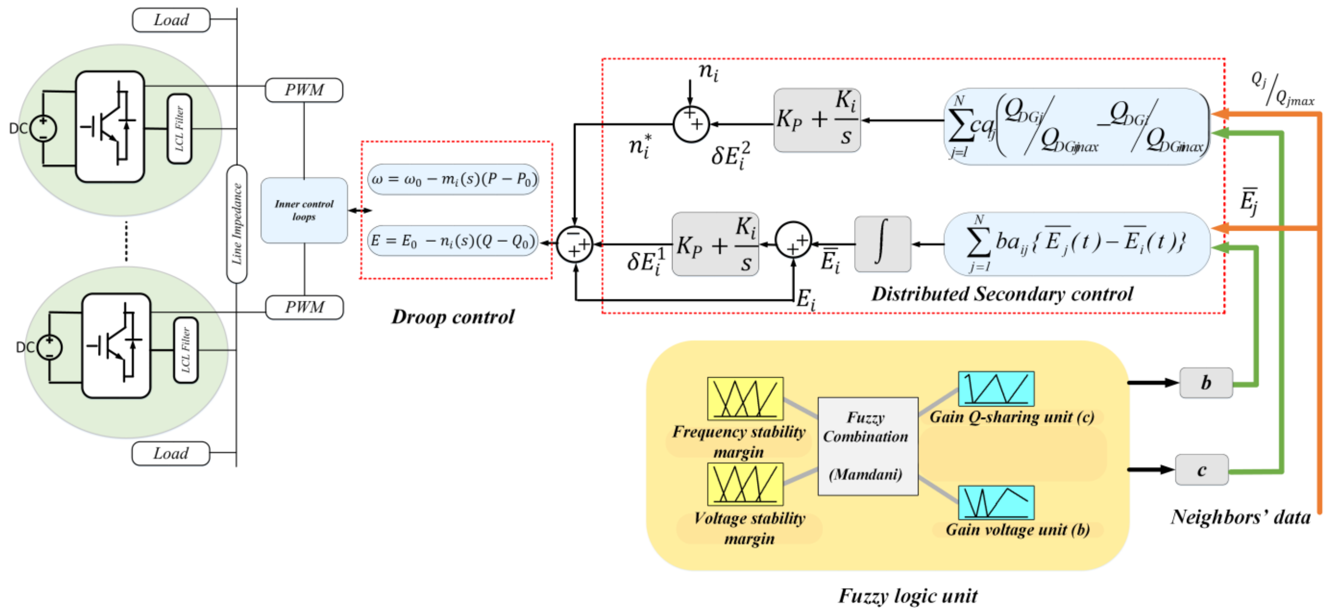


Fig.2. The proposed Fuzzy logic-based distributed secondary control for agent i.

$$\delta E_{DGi}^{2} = k_{pQ}\left(\sum_{j=1}^{N} ca_{ij}\left(\frac{Q_j}{Q_{j\max}} - \frac{Q_i}{Q_{i\max}}\right)\right) \qquad (5)$$
$$+k_{iQ}\int\left(\sum_{j=1}^{N} ca_{ij}\left(\frac{Q_j}{Q_{j\max}} - \frac{Q_i}{Q_{i\max}}\right)\right)dt.$$

where c is gain related to the reactive power regulator and k_{pQ} and k_{iQ} are proportional and integral parameters for the PI controller.

As seen in Fig. 2, both correction terms, i.e., δE_{DGi}^{1} and δE_{DGi}^{2} are added to the Q-V droop mechanism to achieve the control objectives by shifting the droop characteristics up or down.

As already mentioned, a communication network is used to exchange data between the controllers of all DGs. Therefore, defining appropriate communication weights, i.e., consensus parameters is essential for the introduced distributed secondary control. This paper proposes an intelligent method based on fuzzy logic to estimate the consensus parameters.

IV. FUZZY LOGIC BASED ON DISTRIBUTED AVERAGING

System stability depends on consensus parameters. These parameters could increase/decrease the voltage regulation at each DG i. The complex conjugate eigenvalues of (4) and (5) are highly depends on the voltage dynamics. The consensus parameters, i.e., b and c, have high effect on voltage and frequency stability; small variation of these values affects the system stability. In next section, impact of the main parameters is analyzed, and an overall framework will be presented.

A. Relationships Between Stability and Distributed Parameters

To analyze the effect of the consensus parameters, it is necessary to find the range of stability. In this study, the secondary controller is activated at t=12 s and added to droop control. The importance of parameter "b" is described with the relation of voltage and reactive power. The amount of "b" is positive and smaller than 22 ($b \le 22$) which means for amount bigger than 22 the system may be unstable. As shown in Fig. 3 (a and b), the voltage and reactive power sharing of the system would be zero when the secondary control is activated at t = 12 s (stretch line). For amount between 0 and 22, the system is stable (a = 300 and c = 1.98e-4 are fixed).

Increasing and decreasing the amount of "c" has a different impacts on the controller performance, providing different sharing of reactive power among the DGs. This value should be positive and occurs between 2e-4 and 6e-4 in order to have no oscillations. The results show that decreasing the amount of "c" increases the settling time of system response. As clearly shown in Fig. 3 (c to f), the settling time increases for reactive power and voltage, when the secondary control is activated at t = 12 s. Increasing the amount of "c" up to 6e-4 causes intense oscillation, increasing the voltage amplitude and accordingly the system instability. Fig. 3 (c to f) shows the results for c = 9e-4 (a = 300 and b = 0.0073 are constant).

B. Consensus algorithm model training scheme

Due to nonlinear behavior of the system, defining the consensus protocols is not easy by conventional approaches, e.g., trial and error method. In this study, an intelligent Fuzzy logic (FL) method is exploited to estimate the parameters of the proposed consensus protocols. The reason is that FL does not require formulating the mathematical model of the system to define the consensus parameters. FL uses simple mathematics to estimate the desired output. To create an inference fuzzy-rule-based model of the consensus algorithms, a training procedure is used to train the fuzzy system based on the inputs and their impact on stability. Data

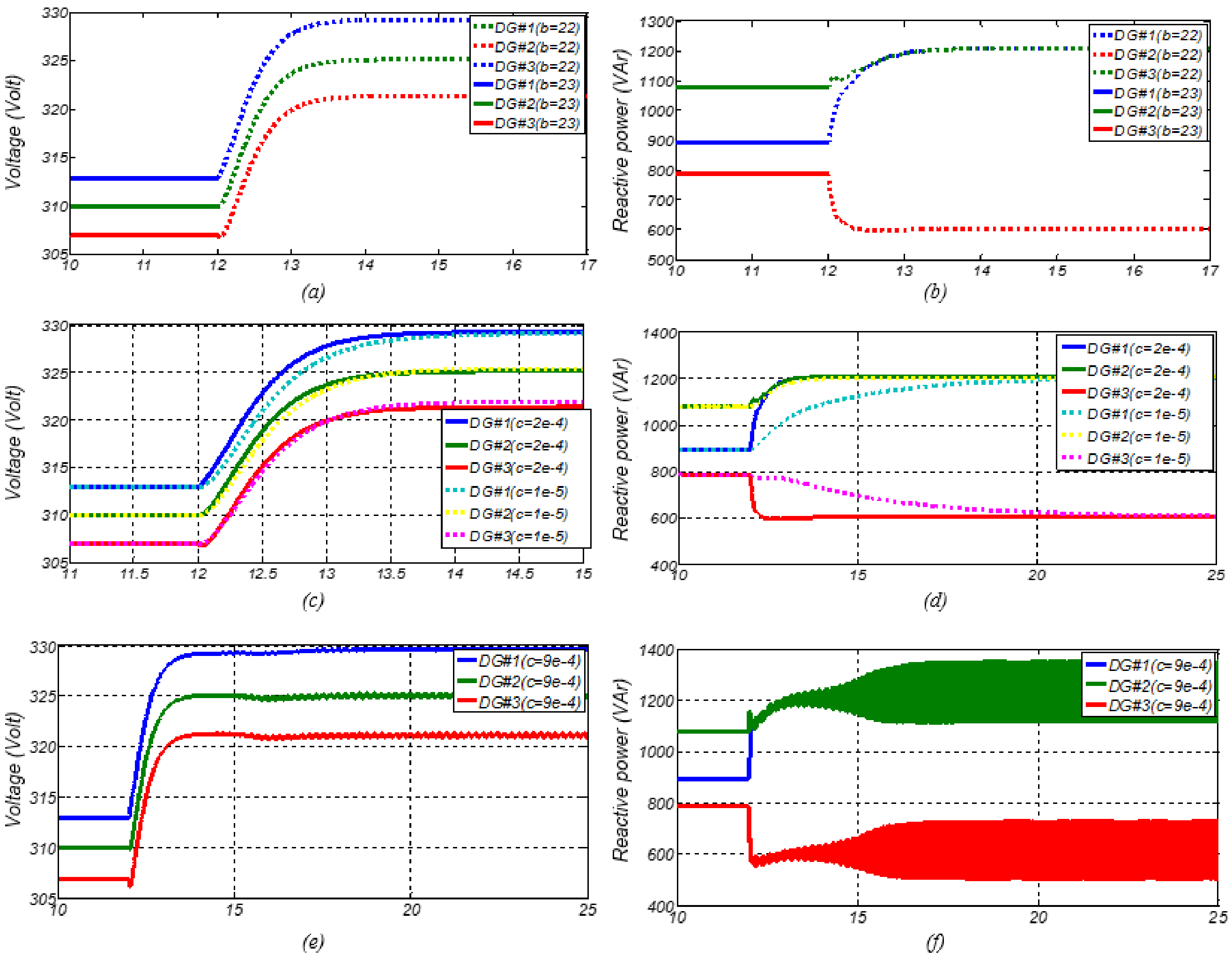


Fig. 3. Impact of coupling gain b (b=22, 23) on the system performance, (a) voltage, and (b) reactive power. Impact of coupling gain c (c=2e-4, 1e-5 and 9e-4) on the system performance. (c and e) voltage frequency, and (d and f) reactive power.

for inputs are based on the difference between the measured and nominal data for frequency and voltage, categorized between zero and one. This means that the fuzzy processor presents a value for frequency and voltage stability.

Each datum used in fuzzy training is defined as (f, v, cp)*, which* f *is the frequency stability margin,* v *is the voltage stability margin and* cp *is the consensus parameter. In this study the datum is defined as fuzzy inputs because of existence non-linear functions. Hence, the training task includes making a fuzzy model from the training data. After training is done, the fuzzy-rule-based defines a function, g, as*

$$\{g:(f,v)\leftrightarrow cp\}. \qquad (6)$$

The training scheme is presented as following:

- *Fuzzifier: In this step, the inputs, outputs and their ranges are defined. The membership functions for inputs and outputs are arranged as not stable (NOTS), very low stability (VLS), low stability (LS), and normal stability (NS). Fig. 4 shows the*

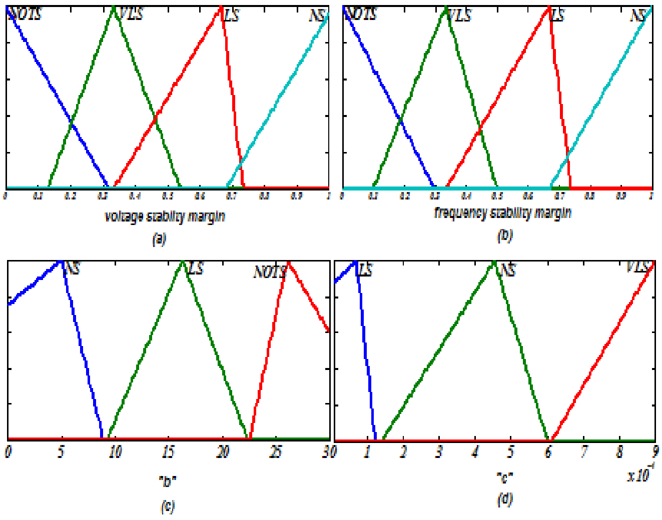


Fig. 4. Membership functions for inputs (a) voltage stability margin (b) frequency stability margin and outputs (c)"b", and (d)"c".

membership functions (MFs) for inputs and outputs limitation of each input and output are given in Fig. 4.

- *Aggregation: The knowledge base for fuzzy logic system is a collection of fuzzy if-then rules as the following form, e.g., rule 15 from Table I explains*

$$R^{15}: \text{If } f \text{ is } \mu_{f(NS)} \text{ and } v \text{ is } \mu_{f(LS)} \text{ then } a \text{ is } \mu_{a(NS)}, b \text{ is } \mu_{b(NS)} \text{ and } c \text{ is } \mu_{c(NS)}. \tag{7}$$

This rule shows that if the degree of MFs (μ_f) for frequency stability margin is NS and for the voltage stability is LS, therefore the results for all outputs are NS. The rules are listed in Table I.

- *Defuzzifier: In this step, the fuzzy outputs are converted to a non-fuzzy values. Hence, the center average defuzzification formula based on triangular is used to determine the crisp outputs, i.e., consensus parameters as*

$$y(x) = \int y_1 \mu_{f1}(x)dx \Big/ \{\int \mu_{f1}(x)dx\}. \tag{8}$$

where the fuzzy system must be defined so that $\int \mu_{f1}(x)dx \neq 0$ for all y_1. The excellence of this method in comparison to other methods is low computational complexity and also has advantages for implementation of estimation procedure in practical real-time.

V. SIMULATION RESULTS

A schematic of the case study is depicted in Fig. 5, includes three DGs interconnected through impedances and local loads placed at all units. Voltage amplitude and frequency are rated in 230 V and 50 Hz, respectively. To reduce the harmonics produced by switching, LCL filters has been used at the outputs of inverters. Impedances among DGs are modeled by series RL branches. A cyber-network is used to share data between DGs' controllers. To show the performance of the proposed approach some scenarios including violent load changes is tested. Matlab/Simulink® is used to simulate the proposed control methodology. Electrical and control parameters of the test case are given in Table II. Adjacent matrix for this case study is considered as

$$A = \begin{pmatrix} 0 & 218 & 0 \\ 218 & 0 & 218 \\ 0 & 218 & 0 \end{pmatrix}, b = 20, c = 0.0004 \tag{9}$$

TABLE I
FUZZY RULE SET FOR OUTPUTS

Rule	Fuzzy variables			
	f	v	b	c
1	NOTS	NOTS	NOTS	NOTS
2	NOTS	VLS	NOTS	VLS
3	NOTS	LS	NOTS	LS
4	NOTS	NS	LS	LS
5	VLS	NOTS	NOTS	VLS
6	VLS	VLS	NOTS	VLS
7	VLS	LS	LS	LS
8	VLS	NS	LS	LS
9	LS	NOTS	NOTS	VLS
10	LS	VLS	LS	LS
11	LS	LS	LS	LS
12	LS	NS	NS	NS
13	NS	NOTS	NOTS	VLS
14	NS	VLS	LS	VLS
15	NS	LS	NS	NS
16	NS	NS	NS	NS

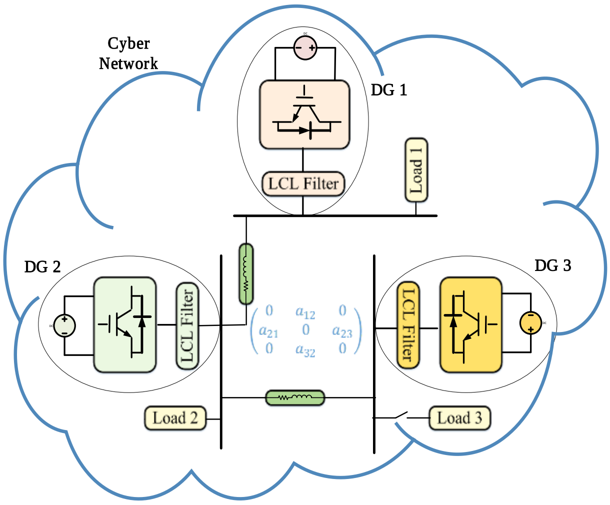


Fig. 5. Microgrid test bench with cyber-network.

To evaluate the proposed method, the system response under frequent load changes is studied. In this scenario, load #3 is disconnected at t=16 s and reconnected at t=22 s. The results for both fuzzy logic-based and conventional methods based on trial and error are shown in Figure 6 (dashed line). This figure shows a case that the system stability is low (LS); it means that the value of fuzzy inputs is 0.6. Hence, the amounts of outputs are estimated as b=16 and c = 5.48e-5. To improve the performance of the controller, the desired values are estimated, considering normal stability (NS) of the system with fuzzy inputs of 0.9. based on fuzzy rules in Table I and the membership functions in Figure 4, , i.e., b=3.69 and c = 0.000399. As Fig. 6 shows, the performance of distributed controller has been improved comparing to the previous case.

VI. CONCLUSION

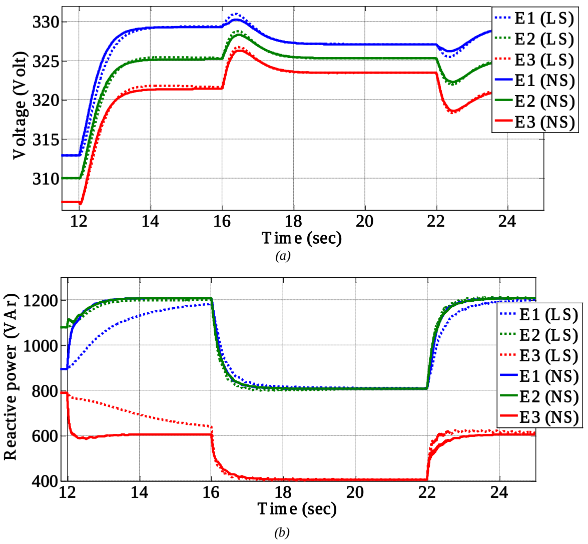
This paper presents a cooperative control framework based on fuzzy logic for voltage regulation and reactive power sharing in an AC microgrids. Dynamic consensus protocol is used to build the proposed distributed control methodology.

With attention to the importance of the main parameters of the cooperative control method, a fuzzy logic is applied to determine the consensus parameters. Simulation results are presented to verify the performance of the proposed approach.

TABLE II

Electrical and control parameters

Parameters	**Symbol**	**value**
Electrical parmeters		
DC Voltage	V_{DC}	650 V
Rated voltage	E_{ref}	320 V
Grid frequency	f	50 Hz
Line impedances 1, 2	$Z_{1\text{-}2}$	$R = 1.2\ \Omega$, $L = 5.4$ mH
Line impedances 2, 3	$Z_{2\text{-}3}$	$R = 0.4\ \Omega$, $L = 1.8$ mH
Load 1, 2	Z_1, Z_2	$300 + j\ 314\ \Omega$
Load 3	Z_3	$150 + j\ 157\ \Omega$
LCL filter capacitance	C	25 μF
LCL filter inductance	L	1.8 mH
LCL filter impedance	L_o	1.8 mH
Control parmeters		
P/f droop coefficient	m_i	0.002 (DG 1, 2), 0.004 (DG 3)
Q/v droop coefficient	n_i	0.01 (DG 1, 2), 0.02 (DG 3)
Rated active power	P_{imax}	1600 W (DG 1, 2), 800 W (DG 3)
Rated reactive power	Q_{imax}	1140 VAr (DG 1, 2), 570 VAr (DG 3)



(a)

(b)

Fig. 6. Smart tuning of the distributed controller using fuzzy logic compared with conventional methods.

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