Decentralized Control System for Participation of Plug-in Electric Vehicles in the Load Frequency Control of a Microgrid

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Abstract—**The penetration level of plug-in electric vehicles (PEVs) has a potential to be remarkably increased in the near future. As a result, the smart power systems will have new challenges and opportunities. The energy storing capability of PEVs is an attractive capability that enables PEVs to participate in providing ancillary services, e.g., load frequency control (LFC). This paper evaluates the participation of PEVs in load frequency control of a microgrid (MG) by using a decentralized multi-agent based control system. According to the proposed multi-agent based scheme, each PEV is considered as an agent that makes a synchronized decision for the participation in the LFC according to the global information. The required global information is discovered through the average consensus algorithm (ACA). The effect of time delay on the proposed method is investigated. Simulation studies are carried out in MATLAB-Simulink and show the effectiveness of the proposed decentralized control scheme.**

Index Terms—**Average consensus algorithm, electric vehicles, load frequency control, microgrid, multi-agent system.**

I. INTRODUCTION

The integration of distributed generation (DG) with a cluster of loads in the power system is related to the novel concept of microgrids (MGs) [1]. Microgrids can operate in both islanded and grid-connected mode. The islanded microgrids in comparison with the conventional power systems are weaker grids with smaller equivalent inertia. This reality makes MGs sensitive to system disturbances and vulnerable to voltage and frequency deviation, especially when the penetration of intermittent renewable generation is high [2].

MGs are controlled in a hierarchical approach in order to enhance the controllability, flexibility and security [3]. The hierarchical control has three levels including primary control, secondary control or load frequency control (LFC) and tertiary control [4]. These control levels differ in terms of time response and communication requirements. Primary control is the first level of the hierarchical control system that has the fastest response and stabilizes the frequency of the MG through a proper load sharing among DG units.

The primary control is not able to entirely adjust the frequency after a perturbation. So, the secondary control is used to omit the frequency deviations in steady state. Tertiary control level manages the flow of power between the MG and upstream grid in the normal connected mode. Also, it has the key functions such as economic managing function and control functionalities that provide optimal scheduling of DG units [5].

Nowadays, due to the high potential of the vehicle to grid (V2G) power, plug-in electric vehicles (PEVs) are considered to be an effective solution to provide support for grid frequency control [6], [7]. PEVs can behave either as generators (in discharging mode) or loads (in charging mode) when they are not in use (on average, an EV is not used for almost 95% of the time for every day [8]). For participation of the PEVs in the grid frequency control, two control schemes exist (i.e. decentralized control and centralized control schemes). The centralized control schemes may incur in single-point-failure. Besides, these schemes are not flexible in adapting to network changes. For example, when new generators or loads are installed in the system, probably the centralized control scheme needs to be redesigned.

In [9]–[13], the role of PEVs in LFC by using a centralized control scheme is investigated. Due to the shortcomings of the centralized control schemes (i.e. single-point-failure and lack of adaptability to the network changes), there is a need for decentralized control schemes.

Decentralized control schemes are suitable to handle a large number of PEVs. Probably the most prevalent decentralized solution corresponds to multi-agent systems (MAS). MAS can bring the benefit of surpassing a single-point-failure. Moreover, the decentralized data processing leads to task distribution, which in turn makes the decision-making process faster [14].

In [15] a decentralized MAS is applied to determine the optimal set-points for PEVs, DGs and loads. PEV agents transmit supply equipment capacity, state of charge (SOC) and connection time to an external agent, named optimization agent, so as to minimize load variance and generation cost.

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In [16] a decentralized MAS-based strategy is presented for congestion management in MGs including PEVs. A multi-agent system shares the local information of agents through communications. Average consensus algorithm (ACA) can solve the problem of communication among the agents. The ACA is a method for distributed sharing of the information in order to reach an agreement on a common decision. Recently, ACA has found many applications in different areas.

This work presents a MAS-based control system for decentralized participation of PEVs in the LFC of a microgrid. In this paper, each PEV is allocated to a given agent. Each agent is only aware of its own information and only communicates with its adjacent agents to discover global information of the system. ACA is used to enable the communication among the agents. A proper control strategy with three control modes based on the microgrid frequency behavior is proposed to determine when the PEV agents should participate in the LFC. When PEVs are required to participate in LFC, they start to share their initial information. After completing the information sharing process, based on the discovered information, all agents make a common decision for the participation of each PEV in the LFC. The effect of communication delay caused by the time consumed for communication among the agents to reach the consensus is also investigated for the proposed method.

The rest of the paper is presented as follows. In section II, the mathematical background is briefly explained. Section III gives an introduction to microgrid frequency control. In section IV, the proposed multi-agent based control system for LFC of a microgrid is presented. Finally, the proposed scheme is simulated in MATLAB-Simulink environment and the results are analyzed in section V.

II. MATHEMATICAL BACKGROUND

A. Distributed averaging

Let's consider $g = (N, E)$ as a graph. N and E indicate the nodes and edges of the graph. Consider in node set $N = \{1, 2, ..., n\}$, each edge $\{i, j\} \in E$ is an unordered pair of dissimilar nodes. Consider c_i^0 as a real number assigned to the node *i*. The average consensus problem is to compute the average $(1/n)\sum_{i=1}^{n} c_i^0$ iteratively at every node in a distributed way (Fig.1). The following equation, known as ACA, is presented for solving the distributed averaging problem [17]:

$$c_i^{k+1} = c_i^k + \sum_{j \in N_i} w_{ij} (c_j^k - c_i^k), \quad (1)$$

where *i=1,2,...,n; n* denotes the nodes number; c_i^k represents the value corresponding to node *i* at iteration *k*, and w_{ij} represents the weight coefficient which allows the communication among the neighboring nodes *i* and *j*. If node *i* is linked to node *j*, $0 < w_{ij} < 1$, else $w_{ij} = 0$. N_i denotes the index of linked to node *i*. In view of $\mathbf{C}^k = [c_1^k, ..., c_i^k, ..., c_n^k]^T$, (1) is presented in matrix form as:

$$\mathbf{C}_i^{k+1} = \mathbf{C}_i^k + \mathbf{A}\mathbf{C}_i^k = (\mathbf{I} + \mathbf{A})\ \mathbf{C}_i^k \rightarrow \mathbf{C}_i^{k+1} = \mathbf{D}\mathbf{C}_i^k, \quad (2)$$

where the identity matrix corresponds to **I**.

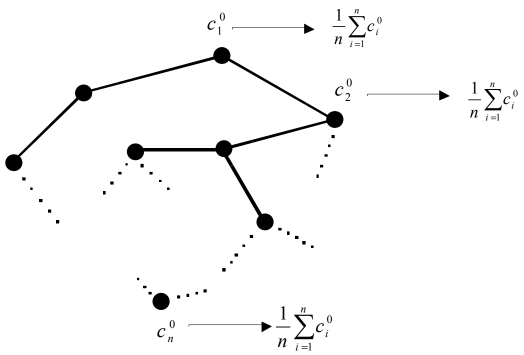


Fig. 1. The principle of distributed averaging.

$$\mathbf{D} = \begin{bmatrix} 1 - \sum_{j \in N_1} w_{1j} & \cdots & w_{1i} & \cdots & w_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ w_{i1} & \cdots & 1 - \sum_{j \in N_i} w_{ij} & \cdots & w_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ w_{n1} & \cdots & w_{ni} & \cdots & 1 - \sum_{j \in N_n} w_{nj} \end{bmatrix}_{n \times n} \quad (3)$$

Matrix **D** is *doubly stochastic* if the sums of each row and column are identical to one and its elements are non-negative, i.e., with $\mathbf{1}_{1\times n} = [1,1,...,1]$, $\mathbf{1} \times \mathbf{D} = \mathbf{1}$ and $\mathbf{1} \times \mathbf{D}^T = \mathbf{1}$ [18]. Eigenvalues of **D**, according to Gerschgorin's Disks theorem, are less than or equal to one. Based on *Perron Frobenius Lemma* [19] :

$$\lim_{k \to \infty} \mathbf{D}^k = \frac{\mathbf{1}^T \times \mathbf{1}}{n}, \quad (4)$$

In the above relation, *n* is **D** dimension. Combining Eq. (2) and Eq. (4) gives:

$$\lim_{k \to \infty} \mathbf{C}_i^k = \frac{\mathbf{1}^T \times \mathbf{1}}{n} \mathbf{C}_i^0. \quad (5)$$

From (5), it can be seen that when k approaches infinity the system reaches the consensus. The design of matrix **D** can determine the speed of convergence. Practically, a precise equilibrium point is not necessary and the number of iterations needed to converge is estimated by:

$$k = \frac{-1}{\log_e(\frac{1}{\lambda_2})}, \quad (6)$$

where λ_2 is the second largest eigenvalue of matrix **D** and *e* is the error tolerance [17]. Eq. (6) indicates λ_2 that decides the number of steps for convergence or identically the algorithm speed. Therefore, the weight coefficients in **D** need to be designed so that λ_2 is minimized to reach the optimum solution and maximum speed.

B. Coefficient Setting

The method which is used to set the weight coefficients vary with the application type (online or offline applications). If the system is subject to configuration changes, at every change an optimization problem must be solved. Due to the multiple constraints and variables in this optimization of the weight coefficients, solving this optimization problem may take a lot of time.

For an online application, a fairly accurate algorithm is required to set the weight coefficients close to the optimum values. In [17] a simple rule named *Uniform* is presented in which the weight coefficients are fixed. The weight coefficients can be computed as:

$$w_{ij} = \begin{cases} 1/n & j \in N_i \\ 1 - \sum_{j \in N_i} 1/n & i = j \\ 0 & otherwise \end{cases}, \qquad (7)$$

In [20] a different method named *Metropolis* is presented in order to increase the convergence speed by applying an adaptive weight updating law, so λ_2 approaches to its minimum value. The updating rule is:

$$w_{ij} = \begin{cases} 1/(Max(n_i, n_j) + 1) & j \in N_i \\ 1 - \sum_{j \in N_i} 1/(Max(n_i, n_j) + 1) & i = j \\ 0 & otherwise \end{cases}, \qquad (8)$$

where n_i and n_j denote nodes number in the neighborhood of nodes *i* and *j*, separately. It can be shown that this method guarantees the two essential conditions in order to apply the *Perron Frobenius Lemma* to **D**.

To show the performance of the proposed method, consider the graph illustrated in Fig. 2. The initial values assigned to the nodes are considered as follows:

$$c_1^0 = 100,\ c_2^0 = 100,\ c_3^0 = -50,\ c_4^0 = -100,\ c_5^0 = -50$$

By using relation (2), for unlimited iterations, the equilibrium point is:

$$c_1^\infty = c_2^\infty = c_3^\infty = c_4^\infty = c_5^\infty = \frac{1}{5}\sum_{i=1}^{5} c_i^0 = 0$$

It denotes that after applying the ACA (Eq. (1)), the ’0’ value is set in every node. Fig. 3 indicates the value of nodes for 60 iterations. The node values converged and reached consensus within 31 and 25 iterations in case of using *Uniform* or *Metropolis* methods, respectively.

III. MICROGRID FREQUENCY CONTROL

Fig. 4 shows the structure of a typical low voltage microgrid. Generally, the MG comprises LV feeders, controllable and uncontrollable loads, microsources (like diesel engine generator (DEG), wind system, photovoltaics (PV), fuel cell (FC), and storage devices (like flywheel and battery energy storage system (BESS)). The microgrid central controller (MGCC), which is placed at the low voltage side of the MV/LV substation, controls and manages the MG centrally. Microsource controllers (MCs) and Load controllers (LCs) have been employed to control the microsources and loads, respectively. They exchange some information (like load/consumption situation, set-points) with the MGCC using a communication link.

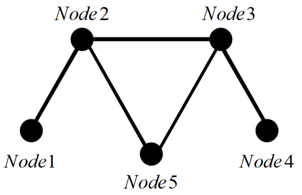


Fig. 2. A typical graph.

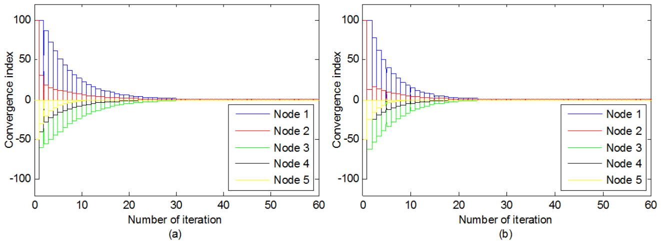


Fig. 3. Comparison of convergence speed for different coefficient setting methods. (a) uniform, (b) metropolis.

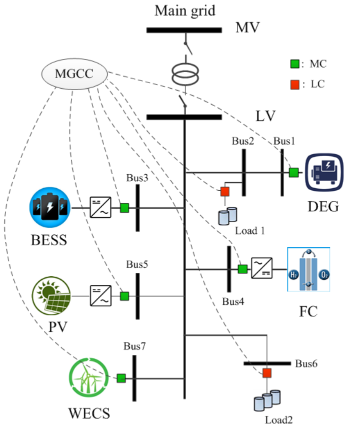


Fig. 4. LV microgrid structure.

LCs are used to control loads through the local load shedding arrangements in conditions of emergency and MCs control the output power of the microsources [21].

Microgrid frequency control would be similar to the frequency control of conventional power systems [22] that is carried out by using various control levels. The control levels are classified into the primary control, secondary control and tertiary control. The primary deals with the inner current and voltage control loops of the microsources. This control level does not need a communication link and the microsources perform it locally. The secondary control or load-frequency control eliminates the frequency and voltage deviation after every change in demand or generation.

Centralized LFC requires a powerful MGCC which is costly, and it can easily suffer from single-point-failure, especially in the case of handling too much information. In the case that there are few sources of secondary reserve in the MG (e.g., DEG) the required information for the LFC are small enough that can be handled with the MGCC. In the case of participation of the PEVs in the LFC as the source of secondary reserve, the MGCC must be prepared to handle a huge amount of information. Decentralized control schemes for LFC can overcome these shortcomings. Hence, this study proposes a decentralized MAS-based control system for participation of the PEVs in the LFC of the MG.

IV. MAS-BASED CONTROL SYSTEM FOR LFC OF A MICROGRID

A. Assumptions

According to the distributed averaging algorithm described before, we assume that the nodes of the graph are considered as specific agents. Also, the edges of the graph are supposed to be the communication links. Each PEV is allocated to a specific agent.

Agents can only communicate with adjacent agents. Applying ACA, agents share their information and discover the global information. Then, they make a common decision for participation in the LFC. In terms of providing secondary reserve, some PEVs are in charging mode and they participate in the LFC just by stopping their charging (one stage participation). Some PEVs are in charging mode and first they stop their charging and then they inject the power back into the grid (two-stage participation). Some PEVs are idle and they participate in the LFC by injecting power back to the grid (one-stage participation). The remaining ones don't participate in the LFC.

B. *Proposed control scheme*

We propose a strategy for participation of the PEVs in the LFC. The presented method depends on the MG frequency deviation and it is consist of three operation modes as depicted in Fig. 5. This figure shows a hypothetical curve of Δf where three operation modes are shown as follows:

- Mode 1: in this mode Δf is in the desired range ($-0.05 < \Delta f < 0.05$) and there is no need for participation of the PEVs in the LFC.
- Mode 2: in this mode, Δf goes out of the desired range and the PEVs contribute to the LFC. The PEVs in charging mode that can stop their charging have the highest priority to provide the secondary reserve. The PEVs that can inject the power back into the grid have the next priority. Each time, one PEV is chosen to participate in the LFC according to its priority till the frequency goes to the acceptable range.
- Mode 3: in this mode, Δf is within the desired range and the PEVs that have contributed in LFC in the previous mode will get their charging situation before they contribute to the LFC. In this case, if $-0.01 < \Delta f < 0.01$ and $d\Delta f / dt < 0.01$, first the PEVs that used mode 2 and now are in discharging mode have the highest priority to be chosen and stop their discharging. Then, the PEVs that were in charging mode before the disturbance will get to their initial charging situation.

The implementation of the above control scheme needs the global information of the PEVs in each mode. The global information is obtained from the local initial information of the PEVs. For each PEV, the local initial information is put in an initial matrix. This matrix only contains the local information of PEV agent. By using the ACA, each PEV agent can access the global information. When the system reaches the consensus, PEV agents make a common decision depending on the operating modes. This process will continue until the MG frequency goes inside mode 1. The following subsection describes the sharing process of the required information of the PEVs for participating in the LFC according to the proposed scheme.

C. *Information sharing process*

If n is the number of PEVs in the MG, each PEV agent can be initialized with $\mathbf{M}$, a $n \times 3$ matrix. In $\mathbf{M}$, up to three non-zero elements can occur. For PEV agent *i*, the non zero elements are $M_{i,1}$, $M_{i,2}$ and $M_{i,3}$. $M_{i,1}$ is the participation index and it is defined as an index to show how many stages the PEV$_i$ has contributed to the LFC after a disturbance.

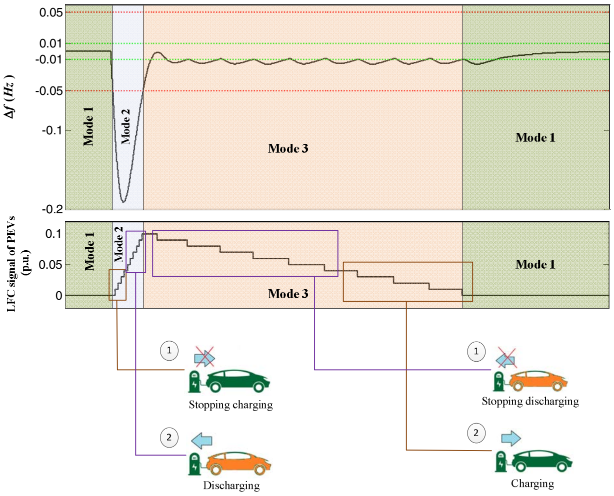


Fig. 5. Concept of the proposed method for participation of PEVs in the LFC.

Hence, $M_{i,1}$ can be 0, 1, 2. $M_{i,2}$ can be 0, 1, 2 to show the priority index of PEV$_i$ agent for participating in the LFC. If PEV$_i$ wants to participate in the LFC by stopping its charging, $M_{i,2} = 1$. If it wants to participate in the LFC by discharging, $M_{i,2} = 2$, otherwise $M_{i,2} = 0$. $M_{i,3}$ represents the amount of charging or discharging power of the PEV$_i$.

For instance, the original matrices $\mathbf{M}_i$, $\mathbf{M}_j$, $\mathbf{M}_n$ for the agents *i, j,n* in mode 2 can be considered to be:

$$\mathbf{M}_i = \begin{bmatrix} 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 1 & P_i^{Charge} \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix}_{n\times3} \quad \mathbf{M}_j = \begin{bmatrix} 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 1 & 2 & P_j^{Discharge} \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix}_{n\times3} \quad \mathbf{M}_n = \begin{bmatrix} 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ 1 & 0 & 0 \end{bmatrix}_{n\times3}.$$

In mode 2, some PEVs want to stop their charging and some of them want to inject the power back to the MG. In the above initial matrices, it can be found that PEV$_i$ has the participation index 0. It means that the PEV$_i$ has not participated in the LFC till now and based on its priority index, it wants to contribute to the LFC with priority index of 1 (stopping its charging) and its charging power is P_i^{Charg}. The PEV$_j$ has already contributed to the LFC in one stage by stopping its charging and now it wants to contribute in the LFC with priority index of 2 (discharging) and its discharging power is P_j^{Disch}. The PEV$_n$ has already contributed to the LFC in one stage by stopping its charging and now it doesn't want to participate in one more stage (discharging). Each PEV agent has the same approach to create the initial matrix.

A characteristic converged matrix is as follows:

$$\mathbf{M}_{conv.} = \begin{bmatrix} \vdots & \frac{0}{n} & \vdots & \frac{1}{n} & \vdots & \frac{1}{n} \\ \vdots & \frac{1}{n} & \vdots & \frac{2}{n} & \vdots & \frac{0}{n} \\ \vdots & \frac{P_i^{Charge}}{n} & \vdots & \frac{P_j^{Discharge}}{n} & \vdots & \frac{0}{n} \end{bmatrix}_{3\times n}^{T}.$$

Based on global information ($\mathbf{M}_{conv.}$), a PEV with priority index 1 that has the highest charging power is chosen and stops its charging.

This is a common decision that is taken by all the PEVs agents. After choosing that PEV and stopping its charging, if that PEV wants to inject power back to the MG, in the next time that this process will be executed, it will have priority 2, otherwise it will have priority 0. When a PEV agent is chosen, its participation index increases one unit. This process will continue until no PEV with priority index 1 exist. Then, the PEVs with priority index 2 will be chosen and contribute to the LFC.

In the mode 3, according to the first column of the final converged matrix, the PEVs which have contributed in the LFC in two stages have the highest priority and they are chosen and stop their discharging. Then, their participation indexes will decrease one unit. After that the PEVs with one stage participation are chosen and will be charged. This mode ends when all the PEVs get to their initial charging situation (all elements of the first column of the final converged matrix are zero).

D. Implementation of the proposed MAS- based control system

The function modules of PEV agent i for participation in the LFC are illustrated in Fig. 6. Each PEV agent has four modules. We consider the following steps for participation of PEVs in LFC:

Step 1) initialization: at first, based on the MG frequency and the decision taken according to the final converged matrix of the previous stage, the operation mode is determined. If the frequency is in the permissible range and according to the final converged matrix and the decision taken in the previous step all the PEVs are in their initial charging situation, the present mode is mode 1 and there is no need for participation in the LFC. In case of mode 2 or mode 3, the local initial information matrix (M_i^0) of every PEV agent is made.

Step 2) information change and update: in this stage, by using the ACA, agents obtain the information of their neighboring agents to update their information. When the global information is discovered (consensus), a common decision is made.

Step 3) decision making: every time an agents attain convergence, based on the operating mode, the participation index and priority index, a proper decision will be taken.

E. Effect of time delay

In terms of the implementation of the suggested algorithm, the speed of the algorithm is a critical issue for this online application.

By neglecting the time that is consumed for initialization and decision making, the time delay of this algorithm is related to the speeds of both the ACA and the communication link.

The estimated time delay is expressed by

$$T = \frac{N_{iteration} \times N_M \times N_b}{C}, \tag{9}$$

where $N_{iteration}$ represents the iterations for convergence, N_M denotes information matrix size, C is communication link speed and N_b represents the number of bits needed to demonstrate the elements of the information matrix.

Assume that a system requires 50 iterations for convergence. If there are 60 PEV agents, $N_M = 60 \times 3$ and for a network speed of 5 Mbit/s, the communication delay is 0.0288 sec. it means every time it takes 0.0288 sec to reach the consensus and choose one PEV for participation in the LFC. The effect of the time delay is considered in the simulations.

V. SIMULATION RESULTS

To evaluate the effectiveness of the proposed decentralized MAS-based control system for participation of the PEVs in the LFC, this method is applied to the LV microgrid depicted in Fig. 4. The frequency response model of this MG is shown in Fig. 7. The MG parameters are given in [23]. The nominal values of the DG units are given in Table I. Table II gives the parameter values of the block diagram. The DEG receives the LFC signal from the MGCC.

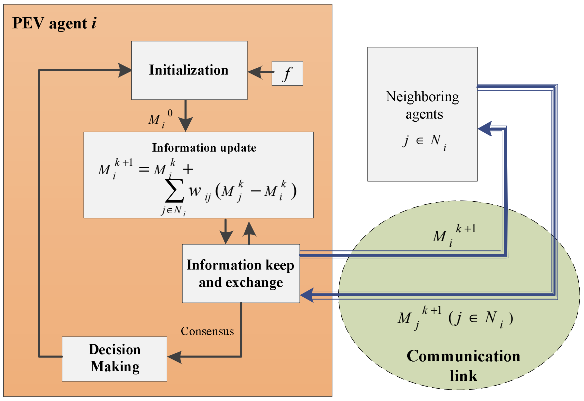


Fig. 6. Function of PEV agent i for participation in LFC.

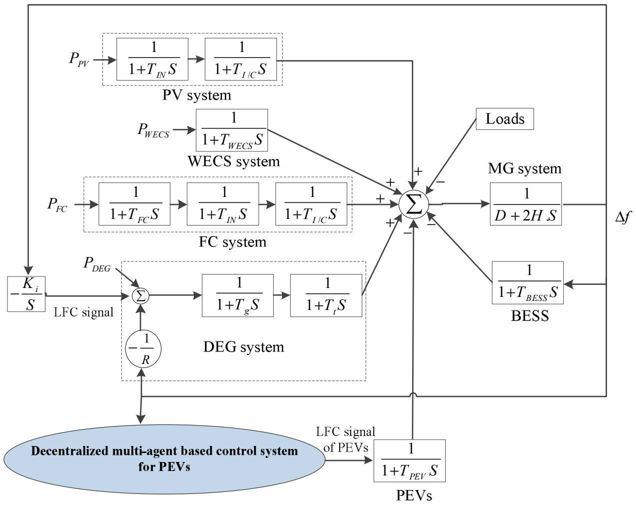


Fig. 7. Frequency response model of the MG.

TABLE I
RATED POWER OF GENERATION UNITS

DG unit	Rated power (kW)
WECS	100
PV	30
BESS	45
FC	70
DEG	160

TABLE II
THE PARAMETERS OF THE STUDIED MICROGRID

Parameter	Value	Parameter	Value
2H (pu s)	0.1667	T_{PEV} (s)	0.05
D (pu/Hz)	0.015	T_g (s)	0.08
T_{BESS} (s)	0.1	T_t (s)	0.4
T_{WECS} (s)	1.5	T_{IN} (s)	0.04
T_{FC} (s)	0.26	$T_{I/C}$ (s)	0.004
K_i (pu/Hz)	1	R (Hz/pu)	3

It is assumed that a special amount of power generated by the DEG is considered as the spinning reserve. The LFC signal of the PEVs is made by the proposed MAS-based scheme in a decentralized way. It is assumed that there are 64 PEVs in the MG and each PEV is assigned to an agent. Fig. 8 indicates the way of connection of agents. We consider two simulation cases as follows.

A. *Case I: Increase in Load*

It is assumed that at t= 15 sec a 30-kW load is added, resulting in a frequency deviation. Before t= 15 sec there are 30 PEVs in charging mode, and 34 PEVs are idle. For simplicity and without sacrificing generality, it is assumed that both discharging and charging power of PEVs are the same and it is 1 kW. Among the PEVs in charging mode, 8 of them can participate in LFC by stopping their charging. Among these 8 PEVs, two of them can inject power back to the MG and among idle PEVs, ten of them can inject power back to the MG. So, after an increment in the load, the first 8 PEVs are used for LFC by stopping their charging and if their reserve is not enough, up to 12 PEVs can be used by injecting power back to the grid.

When the frequency goes out of the acceptable range, the PEV agents (by using ACA) exchange their local information in order to discover the global information. For the topology of Fig. 8 (by using the uniform method), the initial matrices converge in 3787 iterations (0.01 error tolerance). The required iteration for convergence by using metropolis method is 301.

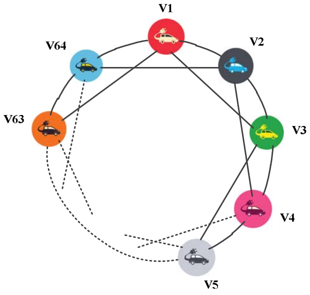
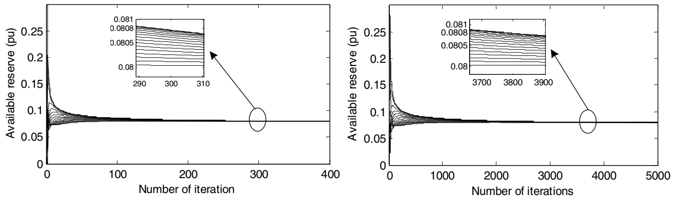


Fig. 8. The way of connection of agents.



(a) (b)

Fig. 9. Available reserve corresponds to the PEVs which want to stop their charging. (a) metropolis, (b) uniform.

Fig. 9 shows the amount of reserve that corresponds to the PEVs which want to stop their charging. Note that the value of base power is considered 100 kVA. We use the metropolis method for determining the coefficients of the ACA.

By using Eq. (11), considering 16 bits for demonstrating the information matrix elements and for a network speed of 10 Mbit/s, the communication delay is 0.0925 sec.

Fig. 10 shows the MG frequency. It can be seen that when the PEVs contribute to the LFC, the frequency nadir is smaller and the frequency is inside the acceptable range in less time.

Fig. 11 shows the LFC signal of PEVs. After the disturbance, when the decentralized multi-agent base controller for the participation of PEVs goes to mode 2, there are 10 PEVs that contribute to the LFC. First, eight of them stop their charging and then two of them go to discharging mode. In mode 2, the width of pulses is equal to 0.0925 sec, which is the delay time for reaching to consensus and choosing one PEV agent. When the conditions of mode 3 are met, the two first PEVs that had contributed to the LFC by discharging, stop their discharging and then the remaining ten PEVs will go to charging mode.

B. *Case II: Increase in Load and Various Time Delay*

The speed of consensus algorithm and the speed of the communication link are two cases that determine the time delay of the proposed algorithm.

The time delay of the proposed algorithm determines the width of pulses in mode 2. Consider that at t= 15 sec a 30-kW load is added to the MG loads.

Fig. 12 presents the MG frequency when different coefficient setting rules for the ACA algorithm are used. Note that in this case, the speed of the communication network is considered 10 Mbit/s.

Fig. 13 shows the LFC signal of PEVs. It can be seen that by using the metropolis method, the PEVs participate in 10 steps in the LFC, while by using uniform methods the PEVs participate only in step 1 in the LFC.

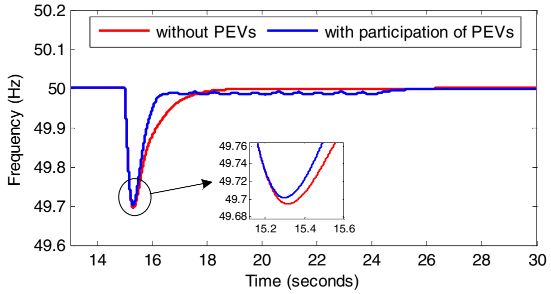


Fig. 10. Frequency response of the MG in case I.

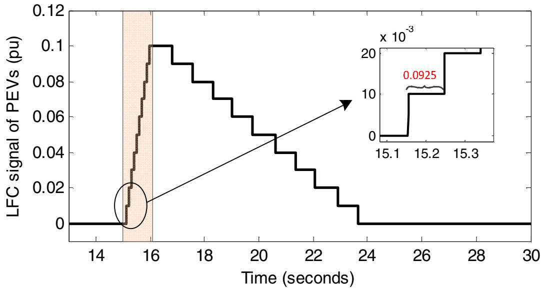


Fig. 11. LFC signal of PEVs in case I.

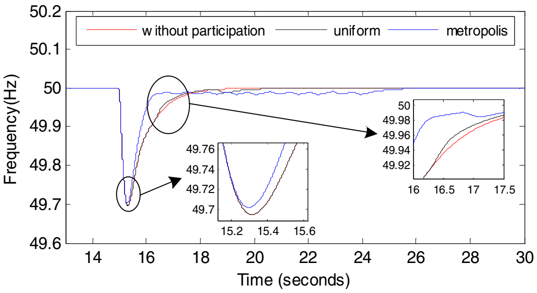


Fig. 12. Frequency response by using different coefficient setting rules.

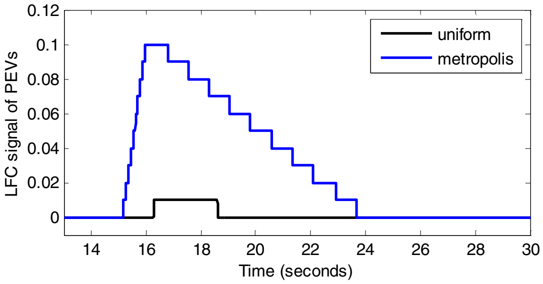


Fig. 13. LFC signal of PEVs in case III.

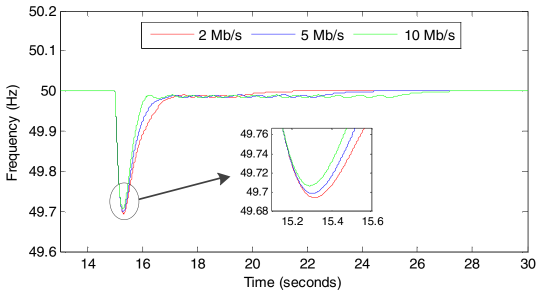


Fig. 14. Frequency response by using different communication links.

The speed of uniform method is not enough to be used in the proposed multi-agent based control system. Indeed, the speed of the communication link can affect the time delay of this method. Finally, Fig. 14 shows the effect of the communication channel speed on frequency response of the MG with the participation of PEVs, using metropolis method.

VI. CONCLUSIONS

This work proposed a new decentralized MAS-based control system for participation of PEVs in the LFC of MG. In the proposed method, all the PEVs were assigned to specific agents. ACA was used as the communication rule to enable the communication among the agents. In this study, an adequate strategy based on the priority index and the participation index of the PEV agents was proposed for the participation of the PEVs in the LFC. The performance of the proposed method considering the effect of time delay was investigated. Numerical results showed the usefulness of the proposed decentralized multi-agent based control system.

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