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Hierarchical Supervisory Control System for PEVs Participating in Frequency Regulation of Smart Grids

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ABSTRACT This paper proposes a two-level hierarchical supervisory control system for plug-in electric vehicles (PEVs) participating in frequency regulation in microgrids with interconnected areas. At the lower level, decentralized fuzzy logic control systems are designed for individual PEVs which locally adjust the V2G power flow rates from each vehicle to the grid according to the frequency deviation in each area and the vehicle's current state of charge (SOC), while maintaining the SOC level above the driver's requested SOC lower limit. At the grid level, a centralized supervisory control system is used to coordinate the injected power from generating units and PEVs based on the grid demand. Simulation results are presented and analyzed to investigate the performance of the proposed two-level system in a network consisting of three interconnected areas populated with PEVs under load disturbances and wind power fluctuations.

INDEX TERMS Frequency regulation, fuzzy logic control, microgrid, PEV, V2G.

NOMENCLATURE

$\Delta P_{Net,i}$	Total generation-load power imbalance in area i
$\Delta P_{mk,,i}$	Change in mechanical power from k^{th} generating unit in area i
$\Delta P_{L,i}$	Load disturbance in area i
$\Delta P_{PEVs,i}$	Total output power from all PEVs in area i
$\Delta P_{tie,i}$	Change in tie-line power in area i
ΔP_{gki}	Change in output power of k^{th} generating unit in area i
Δf_i	Frequency (speed) deviation in area i
SOC_{mi}	Current state of charge of m^{th} PEV in area i
SOC_{mi}^{Ini}	Initial state of charge of m^{th} PEV in area i
SOC_{mi}^{LL}	Requested lower SOC limit of m^{th} PEV in area i
ΔP_{PEVmi}	Output power of m^{th} PEV in area i controlled by the proposed fuzzy logic controller
$T_{Tk,i}$	Turbine time constant of k^{th} generating unit in area i
$TG_{k,i}$	Governor time constant of k^{th} generating unit in area i
T_{ij}	Synchronizing torque coefficient between areas i and j
T_{PEV}	PEVs Time constant
R_{ki}	Droop characteristic of k^{th} generating unit in area i
H_i	Inertia constant of the complete grid in area i
D_i	Load damping coefficient of complete grid in area i
G_{ki}	Generation unit k in area i
K_{PEVi}	Aggregated PEVs gain in area i

I. INTRODUCTION

FUTURE transportation predicts extensive use of plug-in electric vehicles (PEVs) on the roads. On the other hand, microgrids are expected to be the horizons of smart grids where distributed generation (DGs), renewable energy sources and energy storage systems (ESSs) play the main roles. The electric vehicles (EVs) which are parked at parking stations can be seen as distributed energy storage systems with the ability to provide fast ancillary services to power grids. The idea of using the electric vehicle's energy storage capacity in the power grid dates back to 1990s [1]. However, only in recent years, the vehicle to grid (V2G) concept which means the flow of energy from a vehicle to the grid has received attention due to EVs increasing popularity and faster transient response compared to the generator systems [2]–[7]. The main goal of V2G is to provide faster ancillary services by EVs to improve grid performance, reliability and power quality. These services can be as simple as providing power at peak loads to more complex tasks such as frequency regulation, voltage regulation, spinning reserve, compensation for renewable energy intermittency, load balancing and current harmonic filtering [3]–[7]. In a microgrid with distributed load and generation a group of vehicles can help the compensation of the generation-load imbalance and power fluctuations, hence improving grid reliability. With a smart management system, this bidirectional power flow can also reduce the operating costs of the grid. As a result, V2G has advantages both for energy consumers and energy providers. Consumers can make revenue by storing electricity at off-peak hours and consuming the excess energy or selling it back to the grid at peak load hours. On the other hand, various ancillary services from V2G can be beneficial for energy providers using storage capacity of vehicles [8], [9].

One of the most attractive auxiliary services by electric vehicles is frequency regulation. Grid frequency deviates from its nominal value when there is an imbalance between the generation and load. In such situations there must be a regulation process to keep the frequency as stable as possible. This is conventionally done by the automatic generation control (AGC) process which adjusts the generation to the frequency fluctuations or changes in the tie line power by sending signals to control systems of generating units. However, the time constant of most generator systems prevents the fast response required for quick frequency compensation. A possible solution is to utilize the storage capacity of parked PEVs considering the vehicles' battery as distributed energy storage systems in small grids. Since the response time of EV's battery is smaller than generators, if the rate of V2G power flow is controlled, frequency deviations can be compensated and minimized around the nominal value very quickly. However, there exist some obstacles such as battery degradation and infrastructure upgrading costs which must be considered. Information on impacts of V2G on power grid is presented in [2]. It provides general information on system requirements and bidirectional charging/discharging strategies. The literature on V2G ancillary services is mostly devoted to the benefits and costs of the technology including some research on optimal usage of PEVs capacity [7]–[10]. Other references such as [11] and [12] have included PEVs in system cost analysis with vehicle owners being paid for the availability of battery capacity and the amount of injected power to the grid. Considering the luxury of communication infrastructure that can facilitate online frequency monitoring at any node of the grid and assuming that EVs have on board energy management devices which can control the forward/backward flow of energy, some control structures have been recently suggested in the literature for primary or secondary frequency regulation by V2G [13]–[19]. In [13] a decentralized control method is introduced that relies on the EV owner's decisions to either hold the current state of charge (SOC) of the battery or get involved in a smart charging method for frequency regulation. However, it does not include the V2G discharge process as an option. In [14] a centralized PI controller with optimization of controller parameters is proposed for frequency regulation in grids with wind power penetration. To enhance the load frequency control (LFC) process, the vehicle power is tuned by adjusting the V2G gain. However, battery SOC levels are predefined and vehicles are classified in advance based on information that is not easy to access in practical situations. In [15] a decision making method is discussed to disconnect PEVs or discharge their stored energies to power grid. However, the EV injected power rates are constant and not controlled. As a result, the response overshoots in some cases indicating the fed back power is more than the grid demand. In [16] a V2G fuzzy control method is implemented for voltage sag reduction without considering frequency regulation. Reference [17] proposes fuzzy controllers for the compensation of renewable energy intermittency and PEVs are considered as a lumped model (not distributed models as proposed in this paper). A similar lumped EV model is used in [18] for frequency control; however, individual PEVs' parameters such as the current SOC levels are assumed to be equal which is not realistic. In [19] EVs are considered to be equipped with local controllers; however, EV parameters are ignored by sending equal LFC dispatch signals to all EVs. To overcome the system uncertainties, a robust model predictive controller is presented in [20] and [21]. However, to include parameter variations (such as the SOCs of EVs) the controller is extended to a multiple model predictive system for different SOC ranges. This requires SOC information in advance and the PEVs to be divided into groups based on their SOC ranges. A relatively simple decentralized fuzzy-based V2G frequency regulation approach is introduced and tested on a single area power system by Janfeshan *et al.* [22]; however, the effect of tie line power exchanges between different areas and the population of PEVs in each area cannot be investigated with their proposed simple model.

This paper proposes a two-level hierarchical supervisory control system for PEVs participating in frequency regulation of islanded microgrids. The combination of the two level control schemes compromises between communications demand, smooth regulation, drivers' convenience and the stabilization of the grid frequency:

- At each lower level (the interconnected areas), an intelligent decentralized (local) fuzzy logic control (FLC) system adjusts V2G power flow while considering the PEV's SOC level and preventing excess discharge of the battery whenever the SOC hits the requested lower limit.
- At the upper level (grid control center), a centralized supervisory control (CSC) system coordinates the aggregated PEVs' injected power according to the grid

demand with minimum data exchange from the distributed devices (PEVs).

Simulation results are presented, analyzed and compared to investigate the FLCs and CSC performances in a microgrid with three interconnected areas populated with PEVs.

This paper continues as follows: Section II describes the load frequency control and PEV discharge models. Section III explains the frequency fluctuation problem with emphasis on V2G participation in frequency regulation. Sections IV and V present the proposed supervisory hierarchical semi-decentralized V2G control method and detailed simulation results followed by the conclusions.

II. LOAD FREQUENCY CONTROL AND PEV DISCHARGE MODELS

This section describes the generalized load frequency control (GLFC) and the PEV discharge models used for the analyses of this paper. Consider an N-area interconnected power grid with generating units and PEVs in which each area exchanges power with the adjacent areas through the tie-lines (Fig. 1). If for any reason a generation-load imbalance occurs in an area or the tie-line power flow between two areas fluctuates, the frequency will deviate from its nominal value. In such cases, a process called automatic generation control (AGC) will return the frequency back to the normal condition. This is done by propagating an area control error (ACE) signal to the existing generating units. The ACE signal is used by the generating unit's controller to adjust the output power based on the grid demand. Depending on the type of generating unit, the types of the controllers vary. However, the AGC process leads to load frequency control (LFC) and compensation of the frequency deviation. If the grid is small in size and there exists sufficient number of vehicles connected to the grid, the battery storage capacity of parked PEVs can participate in the LFC process.

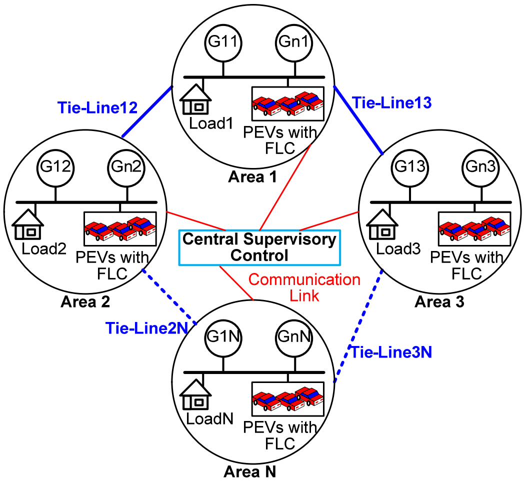


FIGURE 1. Grid with *N* interconnected areas and generating units, loads, and PEVs in each area.

This paper assumes all vehicles connected to the grid have an onboard frequency measurement device that can monitor the frequency fluctuations online and the focus is on an onboard control system which can adjust the discharge rate of PEV's battery based on the real-time frequency measurements.

A. LOAD FREQUENCY CONTROL (LFC) MODEL

To analyze the frequency response of the grid, the model introduced in [23] is used. The original model presents the linear generation-load relationship in a multi-area interconnected grid without any PEVs. For the analysis of this paper, the proposed CSC [Fig. 2(a)], the PEV model [Fig. 2(b)] with the proposed fuzzy controllers [Fig. 2(c)] are added to the original model. The transfer functions of governor and turbine can be the model of gas, wind, thermal or other types of generator turbines. The generating units participate in frequency control based on participation factors. V2G power from PEVs with local fuzzy controllers is aggregated and the power set point $\Delta P_{cei}\mathrm{M}_{\mathrm{ki}}$ (s) is created by the centralized supervisory controller. In this system the generation-load relationship is modeled with inertia and damping component as follows:

$$\Delta P_{Net,i} = 2H_i(d\Delta f_i(t)/dt) + D_i\Delta f_i(t) \tag{1}$$

where $\Delta P_{Net,i}$ is the cause of frequency deviation Δf_i in area i.

The tie-line power is the sum of the net power exchanges between area i and all other areas of the grid (Fig. 1)

$$\Delta P_{tie,i} = \sum_{j=1,j\neq i}^{\Delta P_{tie,ij}} = \frac{2\pi}{s}\Big[\sum_{j=1,j\neq i}^{N} T_{ij}\Delta f_i - \sum_{j=1,j\neq i}^{N} T_{ij}\Delta f_j\Big]. \tag{2}$$

The governor-turbine model of k^{th} generating unit in area i is calculated by $M_{ki}(s)$

$$M_{ki}(s) = \frac{1}{1+T_{Gk,i}(s)} \cdot \frac{1}{1+T_{Tk,i}(s)}. \tag{3}$$

The droop characteristic of the generator is modeled by

$$R_{ik} = \frac{\Delta f_i}{\Delta P_{gki}}. \tag{4}$$

B. PEV MODEL

Different models are used in the literature to simulate the charge/discharge power flow between PEVs and the distribution network according to the source/sink functionality of PEV as a storage device or as a load [13]–[19].

The PEV model used in this paper is shown in Fig. 2(b)-2(c). The total V2G power fed back to the grid is the summation of individual PEVs' power as shown in Fig. 2(b) where m is the number of PEVs and can be different in each area. Each PEV is modeled by its power and SOC limits and it is equipped with a local fuzzy controller that controls the discharge of the battery [Fig. 2(c)]. In this model the power from PEVs in discharge process is limited by the frequency control signal dispatched to each PEV. Each fuzzy controller adjusts the reverse power flow from a PEV to grid by generating a local frequency control signal. The fuzzy controller output is restricted to the maximum power capacity of the vehicle (e.g., -6kW) as long as the battery capacity is above a

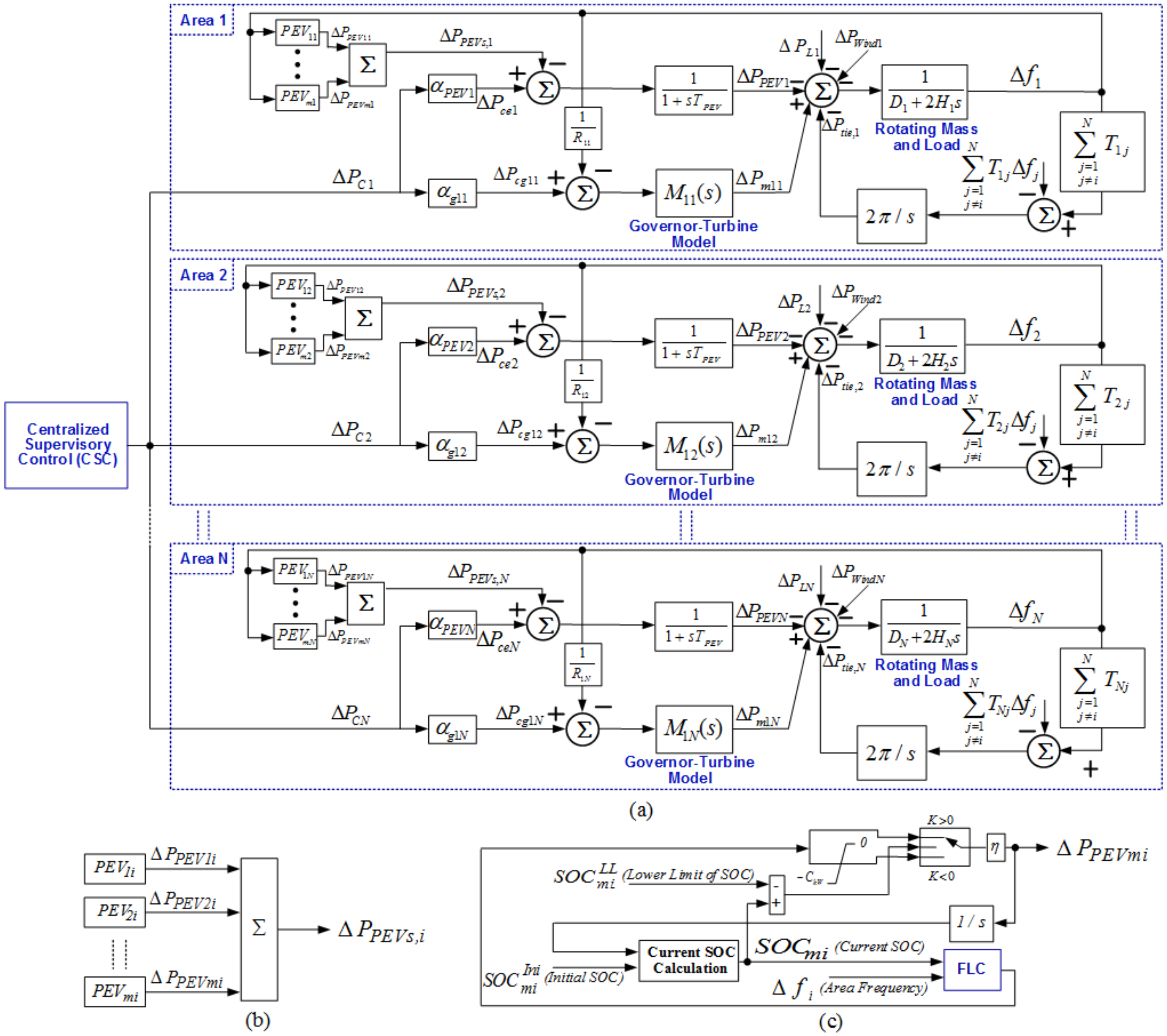


FIGURE 2. Network model of [23] with the inclusion of PEVs: (a) AGC model of a grid with *N* interconnected areas and the proposed centralized supervisory control (CSC), (b) the total injected power from *m* PEVs in area *i*, and (c) the PEV discharge model with the proposed FLC.

lower limit (e.g., 80%). Furthermore, the vehicle will not be discharged when the battery status reaches lower limit set by the driver. Therefore, the SOC will always remain above the requested lower limit to meet the driver preferences for the next trip.

III. GENERATION-LOAD RELATIONSHIP WITH V2G PARTICIPATION IN FREQUENCY REGULATION

The total power flow in each area in the presence of PEVs is described by the following equation:

$$\Delta P_{Net,i} = \Delta P_{m.i} - \Delta P_{tie.i} - \Delta P_{L.i} - \Delta P_{PEVs,i}. \qquad (5)$$

The frequency deviation in each area is calculated by combining (1), (2) and (5) using Laplace transform

$$\Delta f_i(s) = \frac{\Delta P_{m.i} - \Delta P_{tie.i} - \Delta P_{L.i} - \Delta P_{PEVs,i}}{2H_i s + D_i}. \qquad (6)$$

Based on (6), the injected power from all PEVs in each area ($\Delta P_{PEVs,i}$) can compensate the load disturbances in the grid and reduce the frequency fluctuations. The rate of power flow from each PEV is controlled by the proposed decentralized PEV controllers described in the next section according to the generation-load imbalance and the SOC level of each vehicle.

IV. PROPOSED HIERARCHICAL CENTRALIZED-DECENTRALIZED V2G CONTROL METHOD

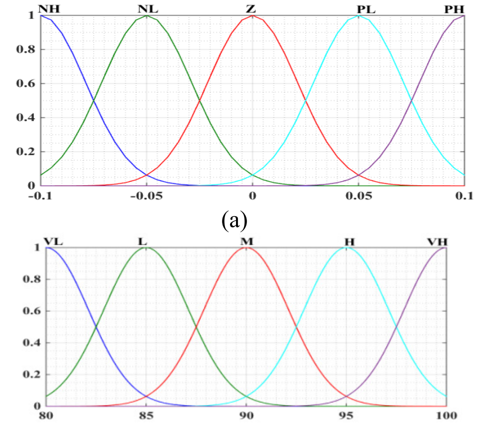
The proposed control scheme in this paper considers two levels of control. The lower level control is a local (decentralized) fuzzy controller for each PEV which is parked at the parking station. This controller adjusts the power flow from EV to the grid based on grid frequency deviation and the SOC of the PEV's battery. The upper level controller is a centralized one which sends the control command to each generating unit and to the PEVs aggregators based on the participation factors and coordinates the power flow in the entire grid.

A. LEVEL I: DECENTRALIZED PEV CONTROLLERS

Fuzzy logic control (FLC) is an intelligent control method which is implemented based on human concept and opinions about a system. It is extensively used in literature for control applications in power systems such as voltage sag reduction [16] and compensating the renewable energy intermittency [17]. The main advantage of FLC is the ability to overcome incomplete knowledge and vague conditions [24], [25]. Since vehicles connected to grid will have different parameters such as initial SOC levels which are unpredictable (the concern of this paper), an intelligent control such as fuzzy logic is a potential candidate for decision making. This paper develops the idea of an onboard controller for each vehicle which can make decisions based on individual PEVs' parameters and preferences. Application of a multi-input knowledge based controller in V2G operation allows for the consideration of the information about SOC levels aligned with the grid regulation demands.

By using an onboard controller for each PEV, a decentralized control method is achieved without requiring any information exchange between vehicles and the grid except for the frequency fluctuations which is accessible at the connection node. In this paper, PEVs are treated as separate subsystems and fuzzy controllers are used to control them independently from each other. The inputs of each fuzzy controller are the frequency deviation and the current SOC level of the participating PEV. The significance of the method is that the vehicle's SOC is monitored online and the local controller prevents excess discharge of the battery whenever the SOC hits the requested lower limit. This will eliminate the requirement of communication with the control center as no information on SOC levels is needed in advance. The output of each FLC is a control signal that adjusts the rate of injected PEV power according to the frequency control requirement.

The proposed FLC is a Takagi-Sugeno-Kang (TSK) controller with two inputs (frequency deviation Δf and the current SOC level) and one output (control signal to adjust PEV output power). For each input, five membership functions are implemented. Different membership functions were examined and the Gaussian membership functions shown in Fig. 3(a)-3(b) led to the best result. The output functions and the corresponding fuzzy rules are presented in Tables 1 and 2.



(a)

(b)

FIGURE 3. **Fuzzy Gaussian membership functions for: (a) Δf (NH: Negative High, NL: Negative Low, Z: Zero, PL: Positive Low, PH: Positive High), and (b) SOC (VL: Very Low, L: Low, M: Medium, H: High, VH: Very High).**

TABLE 1. **Output functions for TSK controller.**

PB:[0 0 -0.00012]	PS: [0 0 -0.00150]	ZO:[0 0 -0.00300]
NS:[0 0 -0.00450]	NB:[0 0 -0.00576]	

TABLE 2. **Fuzzy rules for V2G output power request (Fig. 3).**

Δf / SOC	VL	L	M	H	VH
NH	ZO	ZO	NS	NS	NB
NL	ZO	ZO	ZO	ZO	NS
Z	ZO	ZO	ZO	ZO	ZO
PL	NB	NS	ZO	PS	PB
PH	ZO	ZO	ZO	PS	PB

The proposed local fuzzy controller is implemented at individual PEVs as shown in Fig. 2(c). It is designed so that vehicles with larger current SOCs and smaller requested lower limits inject more power to the grid. The role of PEV model is to keep the SOC above the driver's requested lower limit (e.g., 80%) at all times so that the vehicle has sufficient battery charge for the next trip. Vehicle to vehicle (V2V) charging is prevented during frequency regulation and in this research EVs are not allowed to be charged. This does not affect the performance of the system and the model can be simply modified to allow simultaneous charge and discharge of the PEVs. The fuzzy controller adjusts the control signal (power request) to each PEV based on the area frequency fluctuations, current SOCs and requested SOC limits of that vehicle and hence controls the rate of power injection from each PEV to the grid. As a result, any EV connected to the grid can participate in frequency regulation following a load disturbance while the driver's convenience is also considered by the SOC restrictions.

B. LEVEL II: CENTRALIZED SUPERVISORY CONTROL AT GRID LEVEL

The proposed decentralized controllers can guarantee good performance in frequency regulation. However, since each PEV is equipped with a local controller it is hard to guaranty the frequency stability of the entire grid when number of PEVs increases. Considering this issue, a centralized supervisory control (CSC) system is designed in state space which sends the power set point command to the PEV aggregators. The control command is sent to generating units and

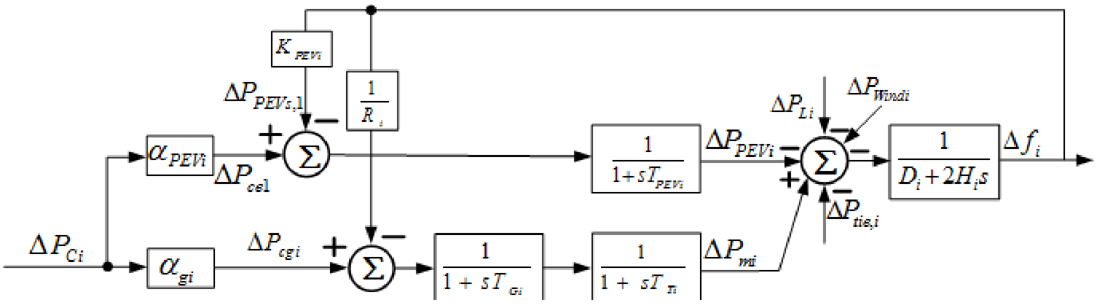


FIGURE 4. **Transfer function model of each control area in a multi-area interconnected grid.**

PEV aggregators based on the participation factors. This can be updated every few minutes based on the state of the grid. Hence, there is no need for large amount of data exchange and fast communications between the upper and lower levels.

The transfer function model of each control area in a multi-area interconnected grid is shown in Fig. 4. In this model aggregated PEVs are modeled by the gain K_{PEVi} which is the average gain of PEV multiplied by the number of available PEVs. The control command P_{ci} is created by the centralized controller while EVs and generating units participate in frequency regulation based on their participation factors. The minimum data from the parking station to the central controller is the number of PEVs available for frequency regulation. The data that it receives is the power set point in coordination with the entire grid generation capacity.

In this paper, the state space control design is used for the central controller which is widely used in coordinated control of power grids [26]–[29].

The state space model for each area in the grid is developed by the following input and output vectors:

$$x_i(t) = \left[\,\Delta f_i(t) y_{gi}(t) P_{gi}(t) P_{ei}(t) P_{tie,i}(t)\right] \tag{7}$$

$$y_i(t) = [\,\Delta f_i(t)]\,. \tag{8}$$

For a network with N interconnected areas

$$x(t) = \left[x_1^T(t) \quad x_2^T(t) \quad \ldots \quad x_N^T(t)\right] \tag{9}$$

$$u(t) = [P_{c1}(t) \quad P_{c2}(t) \quad \ldots \quad P_{cN}(t)]\,. \tag{10}$$

In the above equations, $x(t)$ and $u(t)$ are the input and control command vectors for the proposed centralized supervisory controller where the system is described by

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{11}$$

$$y(t) = Cx(t). \tag{12}$$

Without loss of generality, the matrices A, B and C are introduced for a three-area network here (the same process can be extended for larger networks, in (13) as shown at the top of the next page):

In the state feedback control design

$$u(t) = Kx(t) \tag{14}$$

where K is the state feedback gain.

More information on the smart grid state space modeling based on Eqs. 7-14 is provided in [26] (appendix), [27] (Eqs. 8-11) and [29] (Eqs. 12-19).

In the upper level control with the information of states and the desired performance of the entire grid (locations of poles), the matrix K can be calculated by linear quadratic regulator (LQR) design. This can be done every few minutes to update the control command based on latest status of the grid.

V. SIMULATION RESULTS AND CASE STUDIES

To evaluate the performance of the proposed hierarchical control scheme for PEVs storage capacity as a supplementary reserve, simulations are performed in MATLAB Simulink environment. Simulation results of frequency regulation in a three-area inter-connected grid (Fig. 1) without and with PEVs using three control methods (conventional AGC, proposed decentralized fuzzy controllers without and with the new supervisory CSC system) are presented and analyzed.

Parameters of the AGC and PEV models (Fig. 2) are listed in Table III and the simulation results are presented in Figs. 5-9.

It is assumed that the grid is small, the generators are in the range of 1 MW and during any transient disturbance the system parameters remain constant. In all cases, the LFC model is in per unit (pu) and one generating unit exists in each area. The simulated load disturbance is 0.05 pu in 0.1 second in areas 1 and 2 for Cases A-B (Figs. 5-7) and is increased to 0.2 pu for Cases C (Fig. 8). Case D demonstrates the performance of the control method when a renewable generation unit exists in the grid (Fig. 9). The initial SOC of all vehicles are generated randomly using MATLAB function *randi* in order to realize the actual status of parked PEVs. For each vehicle, the coded function returns an integer value (initial SOC level) between 10 and 100. Without loss of generality, the efficiency of all vehicles is set to 100% and simulation results are presented for 30 seconds to evaluate and compare the transient performance of the proposed method.

Compared with the conventional AGC without PEV participations (Figs. 5, 7-8; broken red lines), the performance of the system is significantly improved. Clearly, inclusion of PEVs with the proposed decentralized fuzzy controllers improves frequency regulation; however, responses contain

$$
A = \begin{bmatrix}
-D_1/M_1 & 0 & 1/M_1 & 1/M_1 & -1/M_1 & 0_{1x10} & \\
-1/R_1T_{G1} & -1/T_{G1} & 0_{1x13} & & & & \\
0 & 1/T_{T1} & -1/T_{T1} & 0_{1x12} & & & \\
-K_{PEV1}/T_{PEV1} & 0 & 0 & -1/T_{PEV1} & 0_{1x11} & & \\
2\pi(T_{12}+T_{13}) & 0_{1x4} & -2\pi T_{12} & 0_{1x4} & -2\pi T_{13} & 0_{1x4} & \\
0_{1x5} & -D_2/M_2 & 0 & 1/M_2 & 1/M_2 & -1/M_2 & 0_{1x5} \\
0_{1x5} & -1/R_2T_{G2} & -1/T_{G2}0_{1x8} & & & & \\
0_{1x6} & 1/T_{T2} & -1/T_{T2}0_{1x7} & & & & \\
0_{1x5} & -K_{PEV2}/T_{PEV2} & 0 & 0 & -1/T_{PEV2} & 0_{1x6} & \\
-2\pi T_{21} & 0_{1x4} & 2\pi(T_{21}+T_{23}) & 0_{1x4} & -2\pi T_{23} & 0_{1x4} & \\
0_{1x10} & -D_3/M_3 & 0 & 1/M_3 & 1/M_3 & -1/M_3 & \\
0_{1x10} & -1/R_3T_{G3} & -1/T_{G3}0_{1x3} & & & & \\
0_{1x11} & 1/T_{T3} & -1/T_{T3} & 0_{1x2} & & & \\
0_{1x10} & -K_{PEV3}/T_{PEV3} & 0 & 0 & -1/T_{PEV3} & 0 & \\
-2\pi T_{31} & 0_{1x4} & -2\pi T_{32} & 0_{1x4} & 2\pi(T_{31}+T_{32}) & 0_{1x4} &
\end{bmatrix}
$$

$$
B = [0 \quad \alpha_{g1}/T_{G1} \quad 0 \quad \alpha_{PEV1}/T_{PEV1} \quad 0 \quad 0 \quad \alpha_{g2}/T_{G2} \quad 0 \quad \alpha_{PEV2}/T_{PEV2} \quad 0 \quad 0 \quad \alpha_{g3}/T_{G3} \quad 0 \quad \alpha_{PEV3}/T_{PEV3} \quad 0]^T
$$

$$
C = [\,1\ 0_{1x4}\ 1\ 0_{1x4}\ 1\ 0_{1x4}\,] \tag{13}
$$

TABLE 3. Generalized load frequency control (GLFC) and PEV model parameters.

Parameter	$G_{1,1}$	$G_{1,2}$	$G_{1,3}$
$T_{Tk,i}$ (s)	0.4	0.44	0.30
$T_{Gk,i}$ (s)	0.08	0.06	0.07
R_{ik} (Hz/pu)	3.00	2.67	2.95
β_i (pu/Hz)	1.0136	1.1857	1.0735
H_i	0.2433	0.2739	0.2392
D_i (pu.MW/Hz)	0.0440	0.0440	0.0460
$T_{PEV,i}$	1.00	1.00	1.00
SOC_{mi}^{LL}	80%	80%	80%

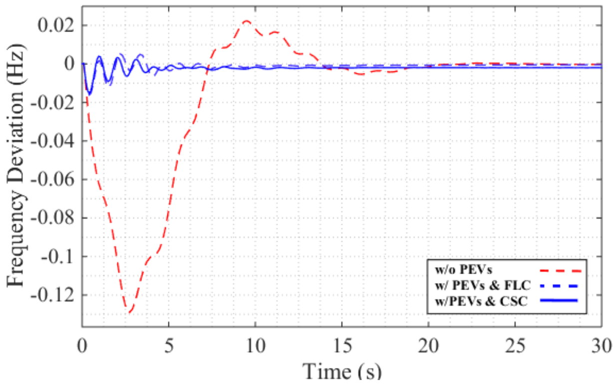


FIGURE 5. Case A: frequency deviation in area 1 with the conventional AGC model (without PEVs), the proposed decentralized FLCs (with PEVs), and the proposed hierarchical CSC system (with PEVs). Moderate load disturbances of 0.05pu (in 0.1 second step) are imposed in areas 1 and 2 with the number of PEVs in areas 1, 2, and 3 equal to 600, 100, and 50, respectively.

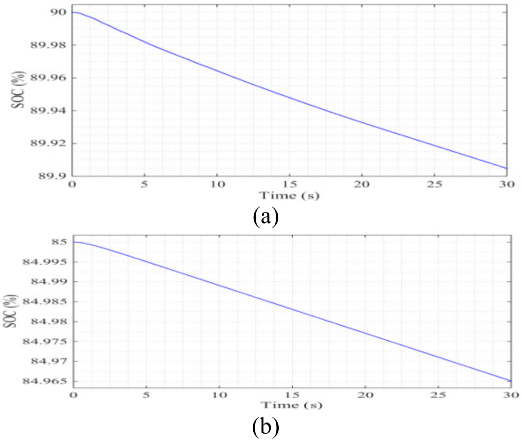


FIGURE 6. Case A: discharge profiles of two selected PEVs with the proposed FLC for the initial SOC values of (a) 90% and (b) 85%.

overshoots (Figs. 5, 7-8; broken blue lines). By adding the proposed hierarchical CSC, system performance is still acceptable while the overshoots are reduced (Figs. 5, 7-8; full blue lines). Note that:

- The generated system responses with different random initial SOCs are similar; therefore, the proposed control method is not sensitive to initial SOC levels of the vehicles.

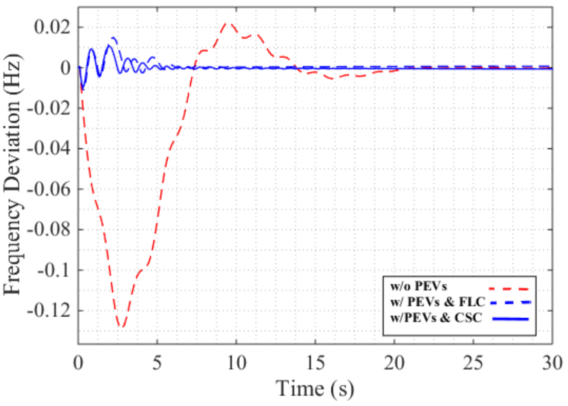


FIGURE 7. **Case B: the same waveforms of Fig. 5 with number of PEVs in areas 1, 2, and 3 increased to 1000, 200, and 100, respectively.**

- Our detailed and extensive simulations indicate that the amount of discharge is not the same for all PEVs when they are controlled by the proposed CSC method. This is a distinguished and desired performance since vehicles should be discharged according to their initial SOC levels considering their requested SOC lower limits (Fig. 6).

A. CASE A: FREQUENCY DEVIATION ANALYSIS

The frequency deviation in area 1 (Δf_1 was analyzed considering the following scenarios (Figs. 5 and 6):

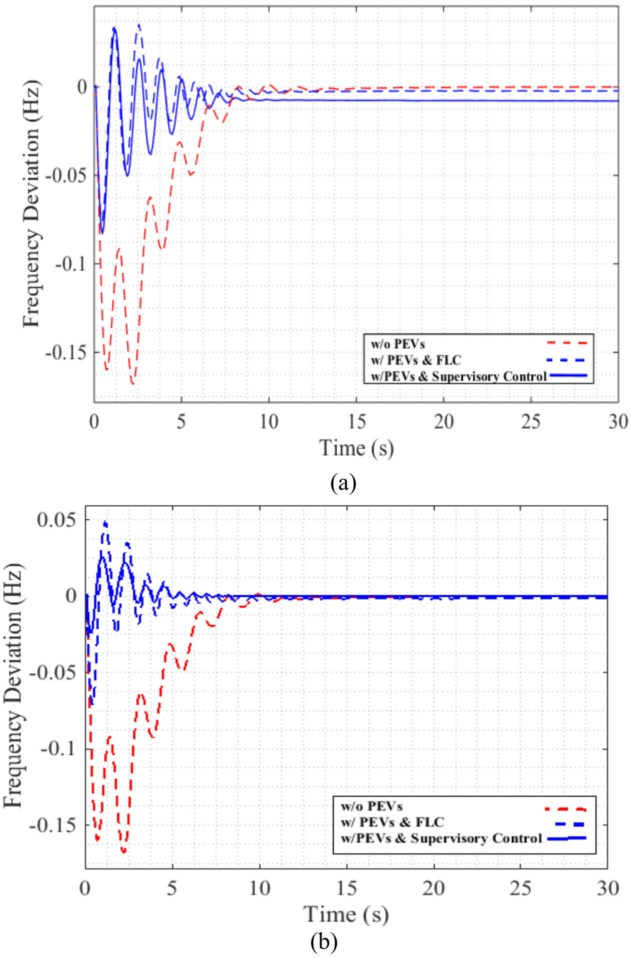
1. The conventional AGC model without any PEVs.
2. The modified AGC model with PEVs and the proposed decentralized fuzzy logic controllers (FLCs).
3. Proposed decentralized fuzzy controllers and the new hierarchical CSC system.

The number of PEVs in areas 1, 2, and 3 are 600, 100 and 50, respectively. Fig. 5 shows the Δf_1 responses for this case.

The proposed decentralized control method successfully adjusts the discharge rate of each PEV and prevents deep discharge of the battery by using the vehicle's initial SOC as an input and making decisions based on the monitored SOC level. To demonstrate the effect of this design, discharge profiles of two selected PEVs with different initial SOC levels of 90% and 85% are shown in Fig. 6. As can be seen with the decentralized fuzzy control, the two vehicles are discharged at different power rates; which is one of the main goals of the proposed controller design.

B. CASE B: EFFECT OF LARGE PEV POPULATION

To analyze the frequency stabilization for large penetrations of PEVs, the frequency deviation in area 1 (Δf_1) is simulated with the number of PEVs in areas 1, 2, and 3 increased to 1000, 200 and 100, respectively. Fig. 7 shows the Δf_1 responses for this case. According to the results of Cases A and B increasing the total number of vehicles (from 750 to 1300) introduces overshoots in the conventional FLC response from 0.003 Hz to 0.017 Hz (Figs. 5 and 7) that may cause instability in grid frequency while the proposed CSC reduces the maximum overshoot from 0.017 Hz to 0.010 Hz.



(a)

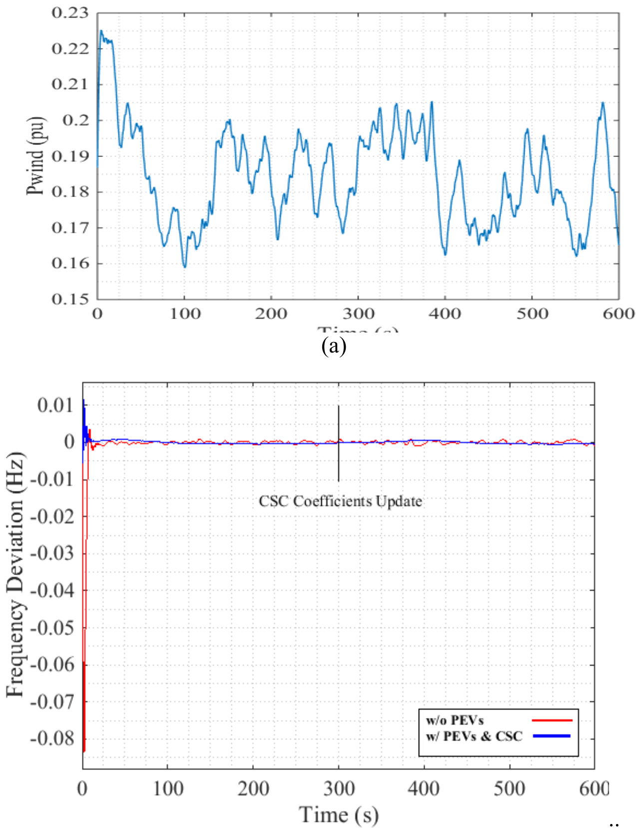
(b)

FIGURE 8. **Case C: Frequency deviation in area 1 with the conventional AGC model (without PEVs), the proposed decentralized FLCs (with PEVs), and the proposed hierarchical CSC system (with PEVs) for a large load disturbance of 0.2pu (in 0.1 second step) imposed in area 1 (a) with 1000, 200, and 100 PEVs in area 1, 2, and 3, and (b) with 1200, 300, and 200 PEVs in area 1, 2, and 3.**

C. CASE C: EFFECT OF LARGE LOAD PERTURBATION

To investigate impacts of load variations, the load disturbance in area 1 is increased from the nominal value of 0.05 pu to 0.2 pu. Fig. 8(a) shows frequency deviations with the same number of PEVs in each area.

According to Figs. 5, 7 and 8(a), the local fuzzy controllers alone are effective in frequency regulation. However, the decentralized control methods cannot guarantee frequency stability in the conditions when a large number of PEVs simultaneously injects power to the grid. The proposed supervisory controller coordinates the amount of total power from different generating units by sending control commands to them (Eqs. 10-14) and guarantee frequency stabilization performance. This causes a damped response with smaller overshoots. To show this, the number of vehicles is increase



(a)

(b)

FIGURE 9. **Case D: (a) wind power output and (b) frequency regulation in area 1 with and without PEVs in the presence of wind source fluctuations.**

to 1200, 300 and 200 PEVs in area 1, 2 and 3, respectively; and the results are presented in Fig. 8(b). Comparison of Fig. 8(a) and 8(b) indicates that if the number of EVs is increased, then the effect of CSC is clearly seen in decreasing overshoot and achieving near zero frequency deviation. Therefore, the proposed hierarchical control method with CSC prevents overshoots of the response and leads to a better result even for large load disturbances.

D. CASE D: EFFECT OF WIND POWER FLUCTUATION

To investigate the performance of the control method in presence of renewable energy sources (here, wind power), the simulation model of a typical wind turbine is used and the output power of the model is added to the grid of Fig. 2.

Fig. 9(a) shows the wind power (pu) and Fig. 9(b) shows the response of the system to a sudden step increase in load (as in Case A) plus fluctuations in the wind generator output power. The CSC control commands to the generating units are updated every few minutes (5 minutes in this simulation) based on the grid status (Eqs. 7-14). The result shows that the system is successful in frequency stabilization in continuous fluctuations as well as step load disturbances.

VI. CONCLUSION

A two-level hierarchical supervisory control system for PEVs participating in microgrid frequency regulation is proposed and tested. It consists of i) decentralized fuzzy logic controllers installed on individual PEVs to adjust the injected power flow from PEVs to the grid for frequency regulation and ii) a new centralized supervisory control (CSC) system installed at the grid control center to coordinate the injected powers from generating units and PEVs based on the grid demand. The proposed fuzzy controllers are designed to adjust the discharge rate of each PEV based on the grid frequency demand and battery SOCs, as well as the requested SOC lower limits to allow for driver's next trip plan.

Detailed simulations and transient analyses are presented for a three-area interconnected grid with PEVs subjected to various load and frequency disturbances. The main conclusions are:

- The proposed decentralized FLCs administered by the new CSC system are effective in frequency regulation as PEV responses are fast and the overall V2G injected powers has extremely improved the frequency regulation of grid.
- The decentralized nature of the proposed FLCs will eliminate the requirement of extrusive communication with the grid control center as no information on SOC levels is needed in advance.
- Load disturbances within few seconds causing frequency deviations from its nominal value are compensated in less than 30 seconds (Figs. 5) which shows that the control method is fast and suitable for transient conditions.
- The control approach is successful in regulating the fed back power from EVs to the grid while also maintaining the SOC levels within the designated limits. The SOC of all EVs remains above the requested lower limits preventing batteries from extrusive discharging (Fig. 6). This is important for driver's convenience and for preventing battery degradation.
- By adding the proposed centralized supervisory control in a hierarchical scheme the response overshoots are reduced and the coordination between PEVs and other generating units in the grid is improved.
- The transient frequency stabilization and dynamic performance are significantly improved compared with the conventional AGC method (Figs. 5, 7, and 8).

This paper does not consider EV charging. The vehicles are assumed to have frequency measurement devices and participate in frequency regulation during their idle time at parking lots when their current SOCs are higher than the expected SOC level for the next trip.

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REFERENCES

[1] W. Kempton and S. E. Letendre, "Electric vehicles as a new power source for electric utilities," *Transp. Res. Part*, vol. 23, no. 3, pp. 157–175, 1997.

[2] M. Yilmaz and P. T. Krein, "Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5673–5689, Dec. 2013.

[3] W. Xiaojun *et al.*, "The application of electric vehicles as mobile distributed energy storage units in smart grid," in *Proc. Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, 2011, pp. 1–5.

[4] A. Hajizadeh, M. A. Golkar, and A. I. Feliachi, "Voltage control and active power management of hybrid fuel-cell/energy-storage power conversion system under unbalanced voltage sag conditions," *IEEE Trans. Energy Convers.*, vol. 25, no. 4, pp. 1195–1208, Dec. 2010.

[5] M. D. Galus, S. Koch, and G. Andersson, "Provision of load frequency control by PHEVs, controllable loads, and a cogeneration unit," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4568–4582, Oct. 2011.

[6] F. R. Islam, H. R. Pota, and M. S. Ali, "V2G technology for designing active filter system to improve wind power quality," in *Proc. Australasian Univ. Power Eng. Conf.*, Sep. 2011, pp. 1–6.

[7] U. C. Chukwu and S. M. Mahajan, "V2G electric power capacity estimation and ancillary service market evaluation," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, Sep. 2011, pp. 1–8.

[8] C. Wu, H. Mohsenian-Rad, and J. Huang, "Vehicle-to-aggregator interaction game," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 434–442, Mar. 2012.

[9] M. Yilmaz and P. T. Krein, "Review of benefits and challenges of vehicle-to-grid technology," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Mar. 2012, pp. 3082–3089.

[10] S. Han, S. Han, and K. Sezaki, "Economic assessment on V2G frequency regulation regarding the battery degradation," in *Proc. IEEE PES Innov. Smart Grid Technol. (ISGT)*, Jan. 2012, pp. 1–6.

[11] T. Ma and O. A. Mohammed, "Economic analysis of real-time large scale PEVs network power flow control algorithm with the consideration of V2G services," *IEEE Trans. Ind. Appl.*, vol. 50, no. 6, pp. 4272–4280, Nov./Dec. 2014.

[12] Z. Luo, Z. Hu, Y. Song, Z. Xu, and H. Lu, "Optimal coordination of plug-in electric vehicles in power grids with cost-benefit analysis—Part I: Enabling techniques," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 3546–3555, Nov. 2013.

[13] H. Liu, Z. Hu, Y. Song, and J. Lin, "Decentralized vehicle-to-grid control for primary frequency regulation considering charging demands," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3480–3489, Aug. 2013.

[14] S. Vachirasricirikul and I. Ngamroo, "Robust LFC in a smart grid with wind power penetration by coordinated V2G control and frequency controller," *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 371–380, Jan. 2014.

[15] Y. Mu, J. Wu, J. Ekanayake, N. Jenkins, and H. Jia, "Primary frequency response from electric vehicles in the great Britain power system," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 1142–1150, Jun. 2013.

[16] M. Singh, P. Kumar, and I. Kar, "Implementation of vehicle to grid infrastructure using fuzzy logic controller," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 565–577, Mar. 2012.

[17] M. Datta and T. Senjyu, "Fuzzy control of distributed PV inverters/energy storage systems/electric vehicles for frequency regulation in a large power system," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 479–488, Mar. 2013.

[18] T. Masuta and A. Yokoyama, "Supplementary load frequency control by use of a number of both electric vehicles and heat pump water heaters," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1253–1262, Sep. 2012.

[19] K. Shimizu, T. Masuta, Y. Ota, and A. Yokoyama, "Load frequency control in power system using vehicle-to-grid system considering the customer convenience of electric vehicles," in *Proc. IEEE POWERCON*, Oct. 2010, pp. 1–8.

[20] J. Pahasa and I. Ngamroo, "PHEVs bidirectional charging/discharging and SoC control for microgrid frequency stabilization using multiple MPC," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 526–533, Mar. 2015.

[21] J. Pahasa and I. Ngamroo, "Coordinated control of wind turbine blade pitch angle and PHEVs using MPCs for load frequency control of microgrid," *IEEE Syst. J.*, vol. 10, no. 1, pp. 97–105, Mar. 2016.

[22] K. Janfeshan, M. A. S. Masoum, and S. Deilami, "V2G application to frequency regulation in a microgrid using decentralized fuzzy controller," in *Proc. 6th Int. Conf. Modelling, Identificat. Control (ICMIC)*, Dec. 2014, pp. 361–364.

[23] H. Bevrani and T. Hiyama, *Intelligent Automatic Generation Control*. New York, NY, USA: Taylor & Francis, 2011.

[24] J. Jantzen, *Foundations of Fuzzy Control: A Practical Approach*, 2nd ed. Hoboken, NJ, USA: Wiley, 2013.

[25] K. Michels, F. Klawonn, R. Kruse, and A. Nürnberger, *Fundamentals, Stability and Design of Fuzzy Controllers*. Berlin, Germany: Springer-Verlag, 2006.

[26] A. Ghafouri, J. Milimonfared, and G. B. Gharehpetian, "Coordinated control of distributed energy resources and conventional power plants for frequency control of power systems," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 104–114, Jan. 2015.

[27] T. N. Pham, H. Trinh, and L. Van Hien, "Load frequency control of power systems with electric vehicles and diverse transmission links using distributed functional observers," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 238–252, Jan. 2016.

[28] S. Bashash and H. K. Fathy, "Transport-based load modeling and sliding mode control of plug-in electric vehicles for robust renewable power tracking," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 526–534, Mar. 2012.

[29] J. L. Mathieu, S. Koch, and D. S. Callaway, "State estimation and control of electric loads to manage real-time energy imbalance," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 430–440, Feb. 2013.

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