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Hierarchical Plug-in EV Control Based on Primary Frequency Response in Interconnected Smart Grid

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Abstract—**The penetration level of the renewable energy resources (RER), such as wind power turbines and solar photovoltaic generation, in interconnected power systems has been increased in many countries. A high penetration level of RERs causes some problems to the grid operator, e.g., lack in primary reserve. Due to environmental concern and energy security risk, many countries around the world decided to increase their electric vehicles (EV) in the near future which provides a good chance to use them as a mobile battery energy storage system (BESS). This paper proposes a new scheme to provide necessary primary reserve from electric vehicles by using hierarchical control of each individual vehicle. An EV aggregator based on the vehicle's information such as the required state of charge (SOC) for the next trip, departure time, and initial SOC is proposed. The proposed aggregation scheme determines the primary reserve and contracts it with system operator based on electricity market negotiation. The effectiveness of the proposed scheme is shown by the several simulation studies in the Taiwan power (Tai-power) system to enhance frequency nadir and steady state frequency after a large disturbance.**

Keywords-component; Vehicle-to-grid; Primary frequency control; primary reserve; smart grid

I. Introduction

Due to the environmental concern, energy security risk, and fossil energy problems, the penetration level of renewable energy resources (RERs) has been widely increased in many countries, e.g., European countries, USA, and Taiwan. Where the high penetration level of RERs in interconnected power system provides new opportunities and challenges to the operator of future smart grid [1]. Uncertainty of RERs causes problem with active power balance and frequency control. Recently, the considerable ability of RERs to provide some ancillary services for future smart grid has been suggested [2].

Each imbalance between active power generation and consumption in power system causes frequency deviation. From the power system security and reliability point of view, the power system operator requires to maintain frequency in acceptable range near to its nominal value (50 or 60 Hz), however frequency control responsible of keeping the frequency in its nominal value by controlling the active power reserve in power grid [3]. Practically, frequency control consists of three control level which are called primary, secondary, and tertiary frequency controls. Primary frequency control reacts very quickly within the first few seconds after disturbance to keep frequency above load shedding frequency point, secondary control activates secondary reserve after primary reserve in 30 sec to 30 min, and finally the tertiary control is responsible of operating the power system in economic and optimal point by re-dispatching generating units. In fact, primary and secondary frequency controls activate their reserve automatically while the tertiary frequency control activates its reserve manually.

Smart grid provides a new ideas in frequency control using demand side management. By using demand response, the more expensive reserve from conventional generating units can be avoided. The demand side can provide secure, less expensive and more reliable primary reserve. However, different types of demand side appliances such as refrigerators, freezers, air conditioners, and water heaters can provide primary reserve to control primary frequency response with the minimum inconvenience to the customers. Electric vehicles (EVs) are attractive type of demand side that can provide a less expensive ancillary services such as primary and secondary reserve by using them as controllable loads [4]. Ref. [5] proposes a new EV control of improving frequency stability in isolated power system. The aggregation model of EV based statistical study for Spanish grid is proposed in [6]. The reference [6] does not use idle EVs to contribute with contingency event which causes lack of primary reserve. An estimation tool of EV demand to participate in primary frequency response (PFR) in Great Britain is proposed in [7]. As mentioned before, EVs are a good choice for providing ancillary services. The number of integrated EVs in power systems in the near future will experience a large increase. However, the contribution of EVs to primary frequency control needs to be more comprehensively investigated.

This paper proposes a new control scheme of the EVs contribution to the primary frequency control in interconnected power systems of future smart grid. In fact, the primary reserve from EVs is determined based on EV's data such as initial state of charge (SOC), the required SOC for the next trip, and the departure time. Also in this paper, a new method of using idle EVs and charging EVs to contribute with contingency event

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TABLE 1. EV GROUPING CONSTRAINTS

	Group0	Group1	Group2	Group3
Charging power [kW]	$p_c = 0$	$p_c \succ 0$	$p_c \succ 0$	$p_c = 0$
soc_{pot} [MWh]	$soc_{pot} \prec soc_{req}$	$soc_{pot} \geq soc_{req}$	$soc_{pot} \geq soc_{req}$	$soc_{pot} \geq soc_{req}$
soc_{inj} [MWh]	Not important	$soc_{inj} \leq soc_{req}$	$soc_{inj} \succ soc_{req}$	$soc_{inj} \succ soc_{req}$

are proposed to mitigate frequency nadir. The rest of this paper is organized as follows: section II describes the proposed hierarchical control scheme of EVs. Aggregation model of EVs for primary frequency response is explained in section III. Section IV presents the simulation scenarios and results. Finally, conclusions of the research study are given in section V.

II. BIDIRECTIONAL COMMUNICATION BASED EV PRIMARY RESERVE FOR PRIMARY FREQUENCY RESPONSE

A. Hierarchical control based EV aggregation

A new Hierarchical control of EVs is proposed to determine primary reserve from integrated EV to the grid. Hierarchical control is part of the Multi agent system, which can be defined as a cluster or group of autonomous, interacting agents sharing a common environment. To practically realize the multi agent control schemes, smart sensor network and actuators are required [8], [9]. Hierarchical based control schemes have been used in a wide variety of engineering fields such as power system protection, automation, and control. In this paper, the hierarchical control scheme is divided into four control levels as follows: a) EV agent is defined as the first multi agent level which refers to each individual EV and the number of agents in this level is equal to the number of integrated EV to the grid, b) concentrate agent which is connected to all the EV agents in its area, c) aggregator agent is connected to all concentrate agents in the interconnected power system, and d) Transmission system operator (TSO) agent is connected to the aggregator agent. This approach requires a two way communication channel between the aggregator agent and TSO, the aggregator agent and concentrator agents, and the concentrator agent and its EV agents.

Each individual EV agent sends its information to the concentrator agent in its area, and the concentrator agent sends the information of EVs interested in provision of the primary reserve to the aggregator agent. The aggregator calculates the reserve available from the EVs in the network. To this end, the aggregator agent needs to obtain the following information about EVs: the initial SOC, the required SOC for the next trip, their rated charging power, and departure time. Then, based on the required primary reserve announced to the aggregator agent by TSO agent, the aggregator agent determines the share of each EV in primary frequency response.

B. Determine Primary reserve of EV Virtual Power plant

To calculate the available primary reserve for the next 20 minutes [10], the aggregator divides the EVs into four groups as follows:

- Group0 consists of all EVs that do not provide primary reserve due to their constraints.
- Group1 consists of all EVs that can provide primary reserve by stopping their charging power after disturbance immediately.
- Group2 consists of all EVs that can provide primary reserve by stopping charging and injecting power back into grid (discharging).
- Group3 consists of all EVs (idle EVs) that can provide reserve by injecting power back into grid.

Based on the constraints in table 1, the aforementioned grouping is done.

Where p_c , soc_{pot} , soc_{inj} , soc_{req} are the EV's charging power, the SOC that the EV can achieve till the departure time, the SOC that the vehicle would have after discharging at the nominal power during the current time step, and the required SOC for the next trip, respectively.

The primary reserve of all EVs based on the above grouping strategy is determined as follows:

$$p_{ev}^{1r} = \left(N_{ev}^{gr1} + 2.N_{ev}^{gr2} + N_{ev}^{gr3}\right).p_{\max} \qquad (1)$$

where N_{ev}^{gr1} , N_{ev}^{gr2} , N_{ev}^{gr3} , $p_{\max}$ are the number of EVs in group 1, the number of EVs in group 2, the EV number in group 3, and the maximum EV charging power, respectively.

In the next step, the aggregator at aggregation center sends the available primary reserve amount and the related bid to the independent system operator. In this way, the aggregator agent participates in ancillary service market as the representative of all EVs. Based on the competitive of the primary reserve in ancillary service market, independent system operator announces the value of primary reserve needed to be provided by EVs to the power network. In the next step, aggregator agent broadcasts the control signal to all EVs in its region through their concentrator agents.

Finally, the control signal comprises adjustment coefficient droop R, primary reserve limits, and frequency dead band for EVs in groups (1, 2) and the activation time response (or frequency activation level) for injecting power into power grid for EVs in groups (2, 3).

III. EV AGGREGATION MODEL BASED ON PFR

The MERGE project of EU countries provides four types of EV which were identified for EU market [11]. Four EV types with their battery information in MERGE database are represented in table 2.

To obtain EV frequency response model, the EV battery charger model is studied. In brief, the EV battery charger consists of an inverter to transform AC power into DC power and a buck converter to step down the voltage and increase the current to an acceptable range for charging EV battery. Practically, the inverter is connected to the power system network through a small inductor (L) and resistor (R_{inv}). Power losses in the inverter is modeled by resistor (R_{loss}). The final model for EV battery charger is shown in Fig.1.

TABLE2: EV CLASSIFICATION BASED ON THEIR BATTERY TYPE.

Classification of EV	L7e	M1	N1	N2
EV charging power [kW]	3	3	3	10
EV battery capacity [kWh]	15	72	40	120

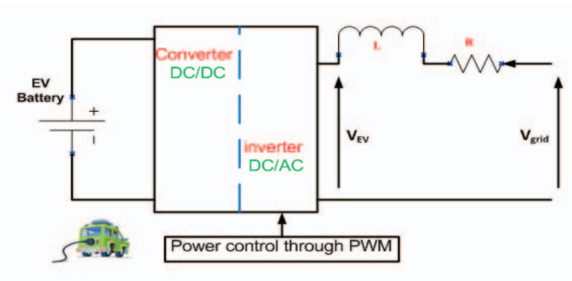

Fig1. Electric vehicle charger model [10].

Fig.1 shows that the inverter is controlled by pulse-width modulation (PWM) switching technique [12]. The active power exchanged between the grid and EV battery would be presented by a differential equation. Therefore the frequency model of EVs is modeled using first order lag function with EV time constant T_{ev} [3]. The EV time constant can be calculated easily as follows:

$$R_{ev} = R_{loss} + R_{inv} \tag{2}$$

$$T_{ev} = \frac{L}{R_{ev}} \tag{3}$$

Depending on the above discussion, in power system frequency studies, EV would be modeled by the first order transfer function:

$$G(s) = \frac{1}{T_{ev}.s + 1} \tag{4}$$

In this paper, T_{ev} is assumed to be 0.05 second. In fact, the EV time constant can be used as a variable number between 35ms and 100ms [7, 13].

Fig. 2 shows the aggregate model of all EVs available in the studied power system. Practically, primary frequency control consists of adjusted frequency droop coefficient R which depends on primary reserve from EV and frequency dead-band with upper and lower power limits [6]. Dynamic block diagram of primary frequency control of aggregation EV model is shown in Fig 2.

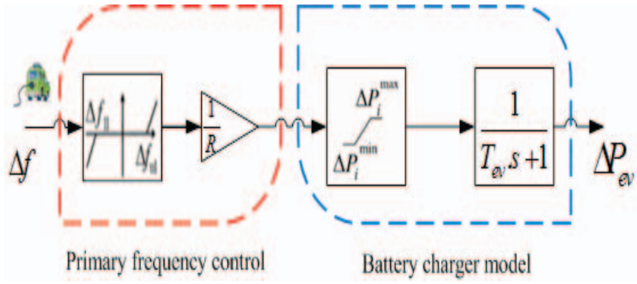

Fig.2. dynamic model of EV for primary frequency control

IV. SIMULATION STUDY

In this section, the proposed method is carried out using EV response to enhance the power system dynamic and reliability. Various scenarios are applied in Tai-power system to improve the dynamic behavior and to avoid unaccepted load shedding.

In brief, the Tai-power system consists of mixed generation unit with high penetration level of renewable energy resources [14-16]. This research assumes that the nuclear power plants and renewable energy resources do not participate in frequency regulation, therefore the dynamic model of Tai-power is adopted from [16]. Reference [15, 16] gives all detail and necessary parameter of the frequency dynamic model of Tai-power grid.

The scenarios of this study in Tai-power system are organized as follows: a) scenario1 describes the effect of EV in primary frequency control when the number of integrated EV in power system is very high, and b) Scenario2 shows the effect of EV in primary frequency response when the primary reserve from EV is very low.

The aforementioned scenarios are carried out in Tai-power system as follows

A. Scenario 1

The first goal is to prevent frequency decline before triggering the under frequency load shedding relay, where the frequency load shedding point is defined as f=59.2 Hz [15]. We assume that the disturbance amount is equal to maximum single contingency and for Tai-power network is calculated [15].

Also we consider the maximum power that each EV can absorb and inject back into grid is equal to 3 kW is. And in this scenario, we assume that the contingency event occurs in time between 1:00 -7:00 a.m. where the number of integrated EV to the grid is so high. Taking in consideration that All EV are equipped with bidirectional charger that can inject energy back into power system network. The table 2 and table 3 present all necessary EV parameters and disturbance information.

The reserve power amount can be calculated easily. Depending on the proposed method the number of EVs in special time that can stop their charging power are 1000, the number of idle EVs that can inject their power back into grid are 500, the number of charging EVs that can stop and inject their power back into the grid are 500, and the number of EVs that cannot participate in the primary frequency event due to their situation such as stat of charging or other problems limitation are 2500.

The primary reserve of EVs in the EV aggregator level is determined as follows:

- the primary reserve of EVs comes from stop charging is calculated as follows:

$$P_{ev}^{stop} = (N_{ev}^{stop} + N_{ev}^{inj}).p_{\max} \quad (5)$$

Where N_{ev}^{stop}, N_{ev}^{inj}, $p_{\max}$, P_{ev}^{stop} are the number of EVs that can stop their charging, the number of charging EVs that can stop and inject their power back into the grid, the maximum charging power limit, and the primary reserve of EVs in the aggregator level by stop charging, respectively.

- The primary reserve of EVs comes from inject power back into grid(discharging) is defined as follows:

$$P_{ev}^{inj} = (N_{ev}^{inj} + N_{ev}^{idle}).p_{\max} \quad (6)$$

Where P_{ev}^{inj} is the primary reserve of EVs in the EV aggregator level by discharging.

- The total primary reserve of all EVs that can participate in primary frequency response is determined as follows:

$$P_{ev}^{1r} = (N_{ev}^{stop} + 2.N_{ev}^{inj} + \mathrm{N}_{ev}^{idle}).p_{\max} \quad (7)$$

Where P_{ev}^{1r} is the primary reserve of electric vehicle in [MW].

Table 3 shows the EVs power participation in primary frequency control to mitigate the effect of contingency on the power system and prevent the frequency decline before reaching 59.2 Hz.

TABLE.3 TOTAL RESERVE FROM AGGREGATOR EV

P_{ev}^{stop} [MW]	P_{ev}^{inj} [MW]	P_{ev}^{1r} [MW]	Response time [sec]
1000	1500	2500	0.05

Scenario1 is divided into two sub-scenarios (scenario1.1 and scenario1.2). Scenario1.1 discusses EVs contribution in primary frequency control using coefficient droop R, and scenario1.2 discusses EVs participation in primary frequency control without coefficient droop.

1) Scenario1.1: EVs contribute in PFC by fixed droop R

This section shows the simulation result of scenario1.1, where the primary reserve of EV is controlled by fixed coefficient droop R. in this study, the fixed droop is set equal to 0.15, the constant time of EV response mode is set equal to 0.05 sec, and also EV dead-band is considered equal to 0.0002.

Note that the largest disturbance is defined as the loss of the nuclear power plant which provides 1900 MW [15]. Fig.3 shows the frequency deviation when the largest disturbance is occurred, maximum deviation (more than 1 Hz) is happened when EVs do not contribute with the contingency event, this frequency decline could trigger the under frequency load shedding relay which it may shed the unexpected and important loads instantly [15].

When EVs contribute with contingency event the frequency deviation will stop before reaching 59.7Hz by using fixed coefficient droop to stop charging without discharging participation. Fig.3 also shows frequency trend when some EVs inject power back into grid where the dynamic performance is improved. And the conventional power plant output is presented in fig.4, where the requested power response of conventional power plant with EVs is reduced.

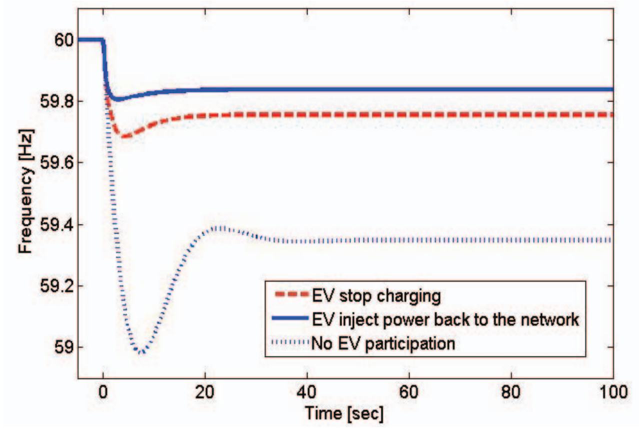

Fig.3 frequency response after disturbance

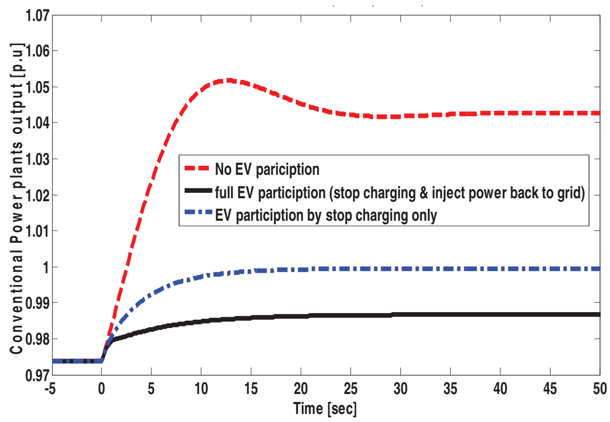

Fig.4 conventional power plant output

EVs demand is presented in fig.5, this figure shows that the EV aggregator demand is fixed and flat when EV aggregator does not participate in primary frequency control, while the EV aggregator demand is decreased to Zero when EVs contribute by stopping their charging. On the contrast, EVs demand is negative when EVs participate with frequency event by discharging.

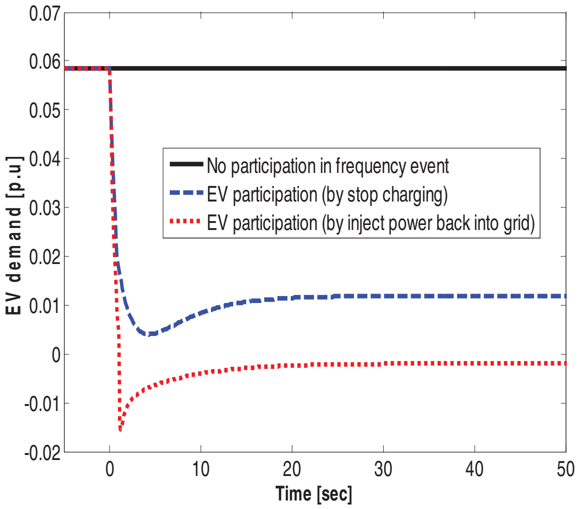

Fig.5. Electric vehicles demand and power response.

2) Scenario1.2: EVs contribute in PFC without adjusted coefficient droop R

In this subsection, the dynamic behavior of power system frequency response model is studied. The frequency control of EVs without frequency droop is considered. As aforementioned in Tai-power guideline, when the frequency drop below 59.7 Hz, the EVs stop their charging instantly. For keeping frequency above 59.2Hz TSO may require to inject power back into grid.

Fig.6 shows the frequency response to the largest disturbance which is defined as nuclear plant loss in Tai-power system. The frequency decline is enhanced when EVs stop their charging power because the reserve from EVs that can stop their charge is sufficient. When the contracted EVs inject their power back into grid, the frequency will come back and cause over response that may trigger over frequency relay or high frequency generation protection relay.

As a conclusion, using EVs or demand response without frequency droop may cause over response and may become as a problem.

B. Scenaro2: EVs contribute in PFC by coefficient droop R when their reserve not sufficient

In this scenario, the power system of Tai-power encounters the largest disturbance when it does not have enough reserve. Where the enough reserve of Tai-power utility to intercept frequency decline before reach to 59.2 Hz is calculated and determined to be 472.5 MW [15]. Also the Tai-power operator needs 575MW to bring frequency above steady state frequency level within 50 sec which is equal to 59.7 Hz.

In this scenario, the available primary reserve from the contracted EVs is 400 MW and is not sufficient to stop frequency decline before reaching 59.2 Hz, the simulation information and results in this case are presented in table 4 and figures 7, 8.

TABLE4. TOTAL RESERVE FROM AGGREGATOR EV

P_{ev}^{stop} [MW]	P_{ev}^{inj} [MW]	P_{ev}^{1r} [MW]	Response time [sec]
200	200	400	0.05

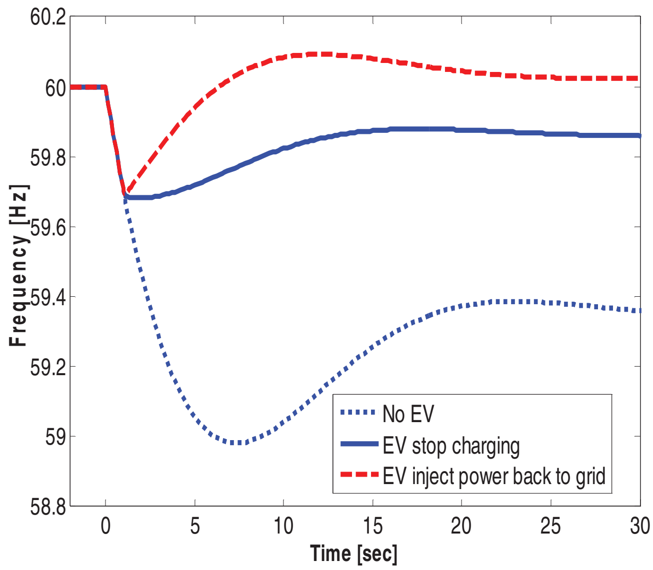

Fig.6 frequency response to the largest disturbance

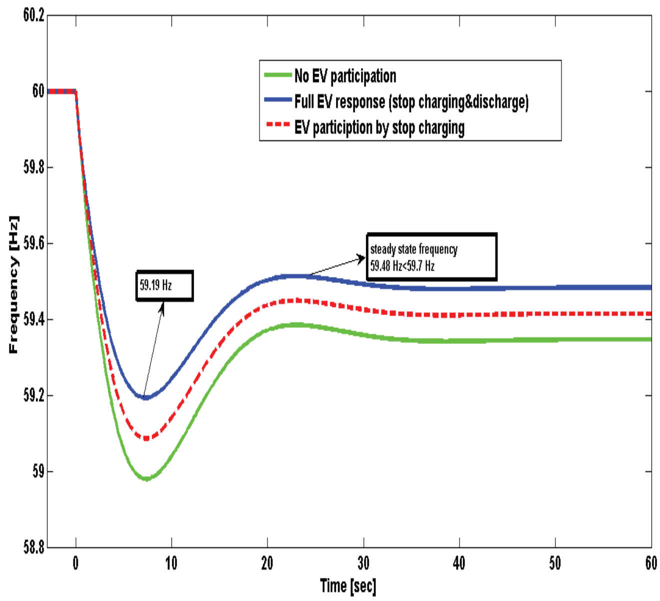

Fig.7. Frequency deviation after the largest contingency event

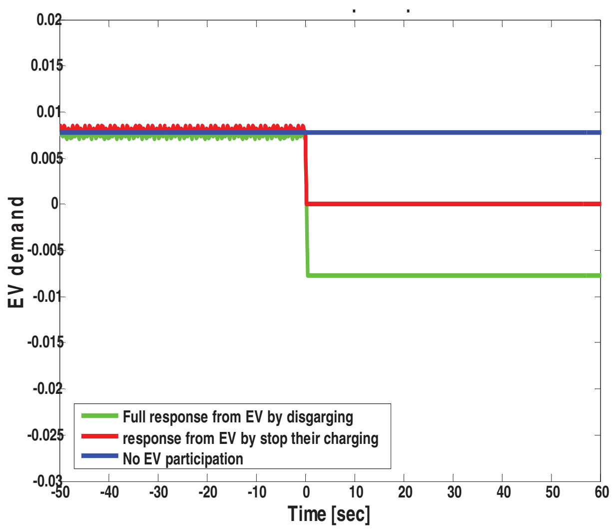

Fig.8. Electric vehicles demand based on their response

V. Conclusion

In this article, a primary frequency response in interconnected system which is one of the important issues was investigated. A hierarchical control scheme of electric vehicles for participation in primary frequency response of a Tai-power system has been proposed. The proposed aggregation scheme based on hierarchical electric vehicles control scheme consists of three agent levels. For the proper operating of the proposed scheme, some information, such as the initial SOC, required SOC for the next trip, and departure time are required. Simulation studies proved the effectiveness of the proposed strategy in primary frequency response for future smart grids. It has been shown that by using the proposed control scheme, not only the frequency nadir is maintained above the minimum allowed value but also the steady state frequency will be brought back to the acceptable level. In addition, due to the fast response of EVs, the other generating units such as hydro unit and conventional power plants will be less stressed for providing primary frequency response. Furthermore, it has been demonstrated that the proposed droop based method is superior to another control method which had been recently proposed in the literature. Also this paper provides a new suggestion to use idle electric vehicles as mobile battery energy storage.

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References

[1] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[2] J. Tomic and W. Kempton, “Using fleets of electric-drive vehicles for grid support,” *J. Power Sources*, vol. 168, no. 2, pp. 459–468, Jun. 2007.

[3] P. Kundur, N. J. Balu, and M. G. Lauby, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994.

[4] P. T. Baboli, M. P. Moghaddam, and F. Fallahi, “Utilizing electric vehicles on primary frequency control in smart power grids,” in *Proc. Int. Conf. Petroleum and Sustainable Develop., IPCBEE*, 2011, pp. 6–10.

[5] J. R. Pillai and B. Bak-Jensen, “Vehicle-to-grid systems for frequency regulation in an islanded Danish distribution network,” in *Proc. IEEE Vehicle Power and Propulsion Conf. (VPPC)*, Sep. 2010, pp. 1–6.

[6] S. Izadkhast, P. Garcia-Gonzalez, and P. Frias, “An aggregate model of plug-in electric vehicles for primary frequency control,” *IEEE Trans. Power Systems*, vol. 30, no. 3, pp. 1475-1482, May 2015.

[7] 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.

[8] L. Dimeas and N. Hatziargyriou, “Operation of a multiagent system for microgrid control,” *IEEE Transactions on Power Systems,* vol. 20, No. 3, pp. 1447-1455, 2005.

[9] D. Fatemeh, and H. Bevrani, “Load–frequency control: a GA-based multi-agent reinforcement learning,” *IET generation, transmission & distribution,* vol. 4, no. 1, pp. 13-26, 2010.

[10] H. Haes Alhelou, M.E.H. Golshan, and M. Hajiakbari Fini “Multi agent electric vehicle control based primary frequency support for future smart micro-grid,” in *proc. smart grid conf. (SGC2015).* Tehran., Dec. 2015, pp. 30-35.

[11] R. Ball, N. Keers, M. Alexander, and E. Bower, Modeling electric storage devices for electric vehicle MERGE deliverable 2.1 of the EU project, 2011.

[12] J. A. P. Lopes, P. M. R. Almeida, and F. J. Soares, “Using vehicle-togrid to maximize the integration of intermittent renewable energy resources in islanded electric grids,” in *Proc. Int. Conf. Clean Electr. Power*, Jun. 2009, pp. 290–295.

[13] S. Jaganathan and W. Cao, “Battery charging power electronics converter and control for plug-in hybrid electric vehicles,” in *Proc. IEEE Conf. Veh. Power Propulsion*, Sep. 2009, pp. 440–447.

[14] L.-R. Chang-Chien, Y. J. Lin, and C. C. Wu, “A real-time contingency reserve scheduling for an isolated power system,” *IEEE Trans. Reliab.*, vol. 56, no. 1, pp. 139–147, Mar. 2007.

[15] *Power System Operation Standards and Manual,* Taipower Power Co.,. Taipei, Taiwan, 2000.

[16] L.-R. Chang-Chien, L.N. An, T.-W. Lin, and W.-J. Lee ,“Incorporating demand response with spinning reserve to realize an adaptive frequency restoration plan for system contingencies’, IEEE Trans. Smart Grid, vol. 3, no. 3, pp. 1145-1153, Sept. 2012.