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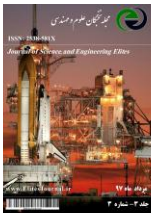

The Impact of Plug-In Hybrid Electric Vehicles on Voltage and Frequency Control of Autonomous Microgrids

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ABSTRACT

This paper proposes a new intelligent droop control for controlling the voltage and frequency of microgrids (MGs). This intelligent method uses ANFIS controllers in order to decouple the system operation from the network specifications (such as line impedances). The proposed framework can be utilized in order to control the MGs including various DG technologies and conventional generators. Also, the PHEVs are modeled and participated in the voltage and frequency control. The PHEVs participate in the primary voltage and frequency control. Simulation studies have been implemented on a 14-bus MG including renewable and non-renewable units. Simulation results approve the effectiveness and applicability of the proposed methodology in control of MG's voltage and frequency.

Keywords: MG, PHEV, Droop Control, Voltage Control, Frequency Control.

1. Introduction

Global trends toward renewable energy sources (RES) and distributed generation (DG) are united to overcome common challenges like global warming, growing energy demands and etc. it has been suggested that overall transition from central generation toward distributed one, is initial necessity. In the other hands, realization of this common goal needs to implementation of the MGs. A MG has been defined as a group of loads and DG units in a small size network, which can operate in both modes; grid connected or isolated [1]–[3]. In grid connected mode of operation, DG units are controlled in the mode of controlling the active and reactive power (PQ), otherwise, in the island mode of operation, DG units are controlled in the mode of controlling the voltage and frequency (VSI) [4]. Droop control strategy has been defined in order to control the inverter based DGs [4], [5]. The basic idea behind the droop strategy is to imitate the operation of conventional governor and AVR in primary frequency and voltage control [6]. Intermittent nature of RES is a challenging item for MGs control and operation. It is proposed that, storage devices can compensate this drawback by their fast and bidirectional response [7]. Because of the fast response of the storages, they can participate in primary voltage and frequency control, besides; a similar argument about PHEVs can be deduced [8]. PHEVs are future options to substitute the conventional cars, in order to reduce the air pollutions. Large battery packs of PHEVs and day growing number of them provide a large storage for the MGs. PHEVs can provide support services like peak shaving, frequency and voltage control [9]. Researches in two aspects are ongoing, the MG's voltage and frequency control methods, and PHEVs modeling and participation strategies. Therefore, the literatures in both directions should be reviewed, concisely. In [10], a novel method is proposed to control the parallel inverters either in islanded or grid connected mode has been proposed. This method mitigates the harmonics and takes the R/X ratio of interface impedance into account. In [11], a new angle droop controller is compared to a conventional droop controller and it is concluded that angle controller shares the power with lower frequency deviation. In [12], a decentralized control method is proposed in order to control the ac single phase microgrids. The proposed method combines droop control with a derivative controller in islanded mode; in addition, a small signal analysis has been presented. In [13] a comprehensive description of the basic droop equations can be found. Then, in order to remove drawbacks of conventional droop method, an intelligent droop control has been introduced, using ANFIS. In [14], a new droop control framework has been proposed in order to enhance the reactive power sharing; this method reduces dependence to the line impedances. In [15]; in order to enhance the MG stability and transient response design of a new virtual impedance has been proposed. Application of this impedance reduces the power oscillations during load jumps. In [16], the steady state frequency deviation as a main drawback of conventional droop method has been removed. In [17] a multi objective two layer control framework has been introduced, PQ units are controlled in the first control layer, and the VSIs are controlled in the 2nd layer. In [18] the frequency and voltage restoration process has been analyzed and a new control strategy has been proposed. In [19] a new robust frequency control method has been introduced in order to develop the secondary frequency control. In [20] a new review of the conventional droop equation is found. This method has several advantages like zero steady state error of frequency. On the other hand, PHEV's model and applications are under investigations. In [21] a new model for the PHEV's charger has been introduced, this model consists of power factor correction unit.

In [22], PHEV's participation in primary frequency control of a MG has been introduced; the PHEV's in this work contribute the MG control strategy by adjusting their charging rate. This work was as a milestone for the other researches. In [23] a dynamic frequency control methodology has been introduced for adjusting the vehicles consumption so as, the frequency deviations will be reduced. In the [24], a novel glimpse to the PHEVs participation problem is presented. Eventually, in the [25] a new power electronic based study of this problem is introduced which contribute the PHEVs in the primary voltage and frequency control. In this paper, following a review of recent researches in the PHEV and MG fields, a new intelligent droop control is proposed to do primary voltage and frequency control of the MGs. The proposed methodology uses the ANFIS as a tool to train the controllers. This method is independent from the lines impedances. The unique characteristic of the proposed strategy in comparison with the previous works is that considers both voltage and frequency of MG and corporate the PHEVs in controlling the both of them. PHEVs modeling and participation in the voltage and frequency control is another prominent contribution of this research. The simulation results show the effectiveness and applicability of the proposed methodology in controlling the voltage and frequency of MG and to participate the PHEVs in this process, effectively.

2. Microgrids Voltage and Frequency Control

A. Traditional droop control

The basic idea behind the droop strategy is that, several generating units in a power system should have different voltage and frequency set points, in order to operate stable [17]. Two conventional droop equations that adjust voltage and frequency set points of generating units are [10]:

$$f = f_n - m_p . P \tag{1}$$

$$V = V_n - n_q . Q \tag{2}$$

Where, the coefficients m_p and nq are called droop coefficients. The f_n and V_n are rated frequency and voltage of the MG, P and Q the active and reactive power of the units. These values typically are determined as [17]:

$$m_p = \frac{f_{max} - f_{min}}{P_{max}} \tag{3}$$

$$n_q = \frac{V_{max} - V_{min}}{Q_{max}} \tag{4}$$

Where f_{max} is the maximum of f, P_{max} and Q_{max} are the maximum of active and reactive power, V_{max} and V_{min} are minimum and maximum of voltage. But, any value of droop coefficients may be in stable or non stable region of operation. So, small signal stability should be done in order to evaluate from the stable values of droop coefficients [6].

B. An intelligent droop control

Two main droop equations are based on this assumption that, the reactance of the lines is much larger than the resistance of them [8]. Several recent researches pass through this assumption and consider both of reactance and capacitances [10], [17], [22]. Here, based on these recent works, an intelligent droop control method is developed. The droop equations in [17] are related to both resistance and reactance of interface lines. Here, in order to eliminate this unfavorable characteristic, it is suggested that, by training controllers, and replacing them with an ANFIS controller, ones can make them independent from the network specifications. At first, consider a simple MG that has been represented in [17]:

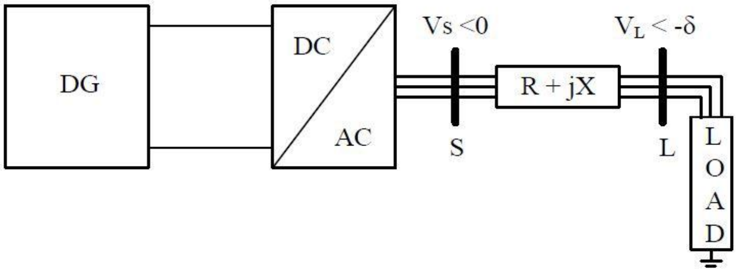

Fig. 1- A simple microgrid consists of a DG, a line, and a load

The proposed droop equations in [17] are:

$$\Delta f = \frac{1}{2\pi}[X.\Delta P - R.\Delta Q] \tag{5}$$

$$\Delta Vs = [R.\Delta P + X.\Delta Q] \tag{6}$$

Where X is inductive, R is resistive. the Δf and ΔVs are inverter frequency and voltage deviations, ΔP and ΔQ are active and reactive power deviations. Considering these equations, for a simple MG like the Fig.1 the values of R and X are apparent, but; for a complex MG including several DGs and loads, these values aren’t as apparent as here are. So, it is suggested that using ANFIS tool, these equations can be removed. So two ANFIS structure is designed as:

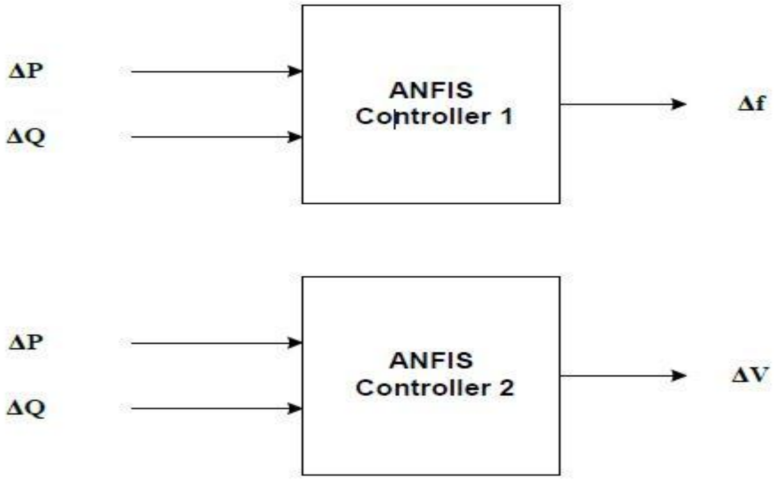

Fig. 2- ANFIS controller inputs and outputs

ANFIS training details has been illustrated in [10], profoundly. So, in order to prevent any tedious descriptions, further details about ANFIS method hasn’t been presented here.

C. The inverter based DGs (IBDG) modeling and control

Any IBDG in the MG consists of a prime mover, a VSI and a filter, as depicted in Fig.3. Control block diagram of the VSI includes several subsystems, voltage controller, current controller, power controller, and ANFIS controllers. Full details of these subsystems are illustrated in [17], [22], comprehensively. So, further description of these units can be found in these references.

3. Phevs model in the MG studies

The model proposed in [21] considers frequency deviations in the control structure so as, the charging power is a coefficient of frequency deviations and derivative of this variable. Anyway, the power set-point is inserted in an interface inverter. This inverter is controlled in PQ mode of operation and receives the power commands [26]. Besides, a DC-DC isolated converter should be considered in the PHEV's model as behalf of the battery charger [22]. The proposed strategy for PHEVs behind the other units (which are controlled by ANFIS controllers) can control the voltage and frequency of MG, effectively. Active power set point in the Fig.4 is determined based on the frequency and voltage of MG, and the mode of PHEVs charging (coordinated or uncoordinated).

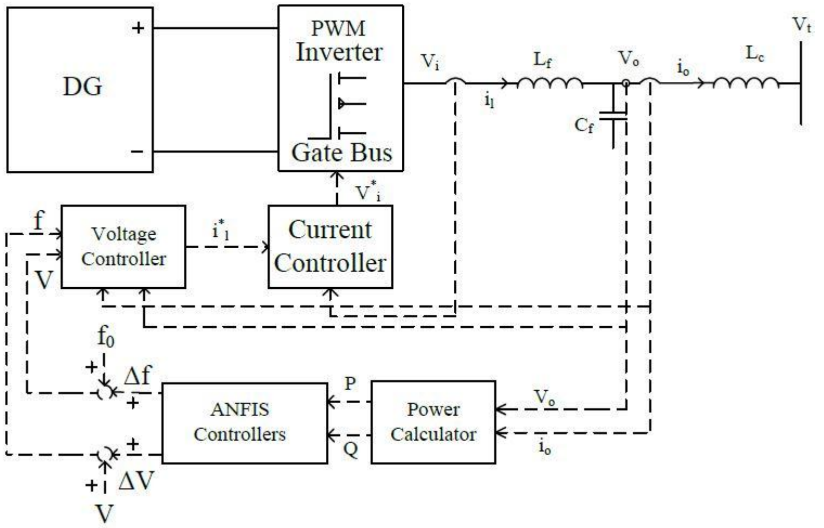

Fig. 3- Proposed control block diagram of an inverter based DG in the MG

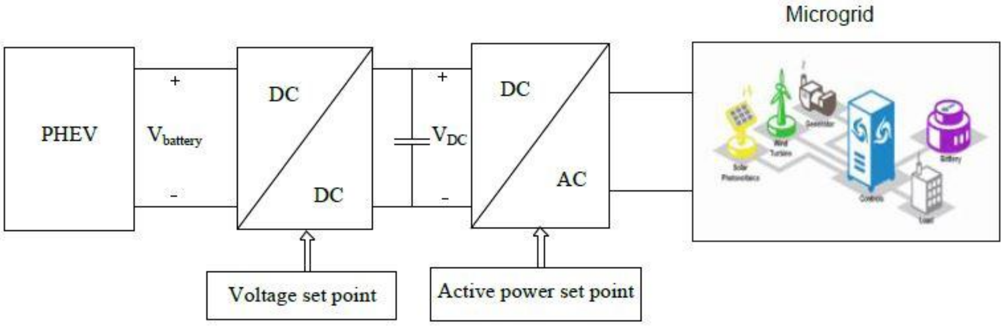

Fig. 4- Proposed Model for PHEV in MG [20]

Considering intermittent nature of RES, storage devices should be available in order to relieve voltage and frequency deviations. Existence of PHEVs in MG can provide a good opportunity to satisfy these needs. The battery of PHEVs that are propagated in the MG, can play the role of DGs storage, and regulate the output voltage and frequency of them. Using the proposed strategy, the charging power or injecting power can be managed. In the other words, we have a type of intelligent or coordinated charging.

4. Simulation and results

In order to implement both proposed strategies of voltage and frequency control and PHEVs participation, simulation studies are presented. Initially, a 14-bus test MG is implemented in the MATLAB/ Simulink 2017a software. Full data about this MG can be found in [10]; Except, the load of all buses are multiplied by 4.5, the Schematic diagram of this MG is illustrated in Fig.5, that consists of DGs and loads and parking lot of PHEVs.

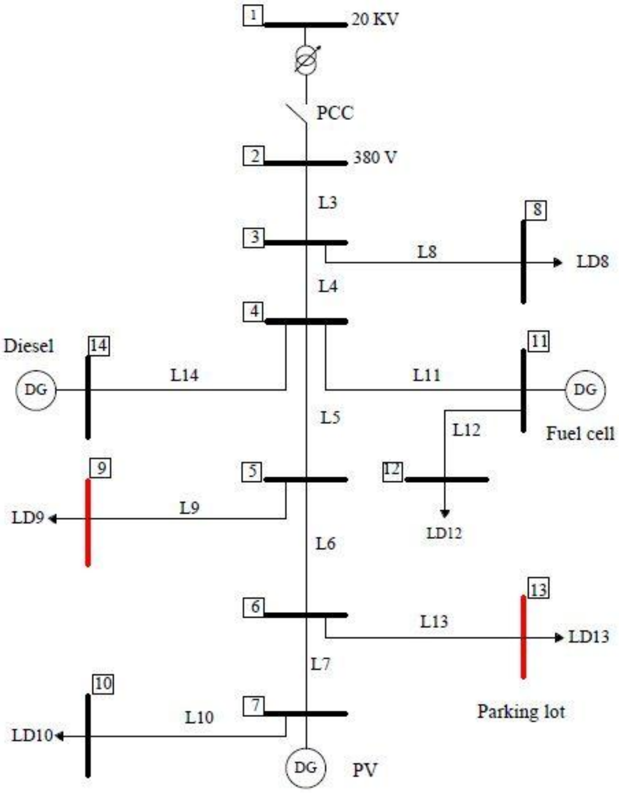

Fig. 5- 14-bus test MG implemented in simulation studies [10]

All of DGs are controlled by an intelligent droop control introduced earlier, and the diesel generator has conventional governor and AVR systems. Two PV array is selected from the library of MATLAB 2017a; Sun Power SPR-415E-WHT-D with 88 parallel string and 7 series connected modules per string. These PV units are connected to bus #7 via a three level neutral point inverter.

Similarly, two PEMFC are connected to the bus #11 via a three level inverter. These fuel cell units are chosen from the MATLAM library both of them are PEMFC-50kW-625Vdc.

Both PV and Fuel Cells are connected to the MG via inverters, for the case of simplicity, all of the inverter's parameters are similar to those introduced in [22] and the ANFIS controllers have been designed based on the method presented in [10] by tools box of MATLAB.

The Diesel generator is a 100kW, 380V, 50Hz unit that is selected from the library of the MATLAB 2017a software.The PHEV model introduced in Fig.4 has two converter, the parameters of the inverter are listed in Table I:

Table I- The Parameters of the Inverter Used in the Phev Model

Parameter	Value
Input voltage of inverter	500 V
Resistance of interface impedance	0.75 Ω
Reactance of interface impedance	0.01 Ω
d-axis compensator component	375 + (250 / s)
q-axis compensator component	375 + (250 / s)
Feed-forward transfer function (Gff (s))	$1/(8\times10^{-3}s+1)$

Maximum active power of parking lot is about 80 kW that is installed in bus #13. Another converter is a DC-DC isolated converter that regulates the input voltage of inverter. But, because of short duration of our scenarios, an ideal dc source is used instead of a battery in addition to a dc-dc converter, because the battery's voltage is relatively constant during this short period of time. Simulation assumptions are:

- ✓ PHEVs in the V2G mode, participate in the voltage and frequency control.
- ✓ Uncertainty of solar irradiance is considered
- ✓ The interface inverters are limited with respect of transmitted current.
- ✓ The MG is autonomous (PCC breaker is open) and the voltage and frequency is controlled by DGs and PHEVs.
- ✓ PV units have storage devices in order to cover their uncertainty.
- ✓ DGs in the MG are controlled by the proposed intelligent droop control.

Three different scenarios are applied to the MG, a load change of P=70 kW at t=3s; a step change from 200 to 50 in the solar irradiance; finally, outage of the fuel cell unit at t=8s. Following this events, DGs are responsible for doing primary frequency and voltage control and to keep the stability of MG.

A. Frequency of the MG

In the Fig.6, frequencies of MG buses have been illustrated. As it can be seen, at t=2s the PHEVs parking is activated in the mode of V2G. A negligible frequency deviation is resulted in this instant; but, because of the nature of constant-speed governor and the proposed droop control, the frequency is restored. Then, at t=3s, because of a severe load change, the frequency of MG decreases about 0.15 Hz. Then; at t=5s solar irradiance is changed, but; because of the storage device operation, any frequency deviation isn't visible in the Fig.6. Then, at t=8s fuel-cell unit is exited. As it is visible in the Fig.6, the MG could remain stable in this scenario, fast injection of active power by PHEV's parking is the key agent of stability, surely. The frequency deviation at t=8s is about 0.25 Hz that is acceptable in related standards. Also, slow response of Diesel with respect to the other units is clear.

B. Voltage of the MG

In the Fig.7, the voltages of DG's buses and the bus which has the load change are illustrated. As the voltage of buses should be near the nominal value of 220 V, the voltage set points of Diesel and fuel cell are set to 1.1 p.u. at t=2s the PHEVs parking is activated and started injecting the active power. At t=3s, a small decrease in the voltage of bus#9 is seen that is the result of load increasing. As, just the primary voltage control is considered, so the voltage drop is inevitable. Then, at t= 8s the fuel cell unit is out of generation. Nevertheless, fast injection of active power by PHEVs parking could stabilize the MG in this severe event. The steady state voltage drop should be removed in secondary voltage control, which is out of scope of this study. It should be noted that, in oppose to traditional power systems, the MG's voltage can be controlled by both active and reactive powers injection.

C. Generated power of DGs

In the Fig.8, the generated powers of units in the MG are illustrated. At t=2s, since the V2G injection has been commenced, PV generation power is reduced about 25 kW.

Fast response of PV system's storage didn't let to the other units to response to this event. At t=3s, a load change of 70 kW is occurred in the bus #9, subsequently, the PV storage and the Fuel Cell are responded to this change and the Diesel didn't sense this happening, because of the nature of its governor and AVR. The reactive power generation of the units is negligible because any reactive load isn't switched. Then, at t=8s, Fuel Cell unit is exited, so diesel unit is generated more reactive power to compensate severe voltage drop, besides; in order to equalize the reactive power generation, the reactive power of PV unit is reduced. In the case of active power, diesel unit couldn't sense the change truly and its response is slow, so its share of active power is small. Preserving the MG stability by injecting a small value of active power (about half the capacity of Fuel-Cell power), from PHEV to MG, is a unique attainment for this scenario.

D. Injected power of PHEVs parking

In the Fig.9, the injected active power of PHEVs parking is depicted. The PHEVs parking starts V2G at t=2s, by about 28 kW power injection. At t=3s that a load change is occurred, fast injection of active power is started and following the frequency restoration, this power injection returns to its contract value (the contract between parking owner and system operator). At t=5s any power injection isn't seen, because of suitable operation of PV's storage. At t=8s, subsequent to Fuel-Cell exit, both frequency and voltage drop, instantly. So, the parking senses this change and increases its injection up to 78 kW. This fast response of PHEVs parking rescues the MG from the instability problem. A frequency deviation and voltage deviation of about 0.03 Hz and 5 V have been considered for the parking activation. Peak injection of parking occurs at t=8s due to simultaneous drop of frequency and the voltage. After operating of the parking, the steady state value of frequency is 50 Hz, exactly. Because the secondary voltage control isn't considered in this study, steady state voltages are under the nominal voltage of the system. In secondary voltage control, by adjusting the voltage set-points of the units, the voltage will be restored to its nominal value.

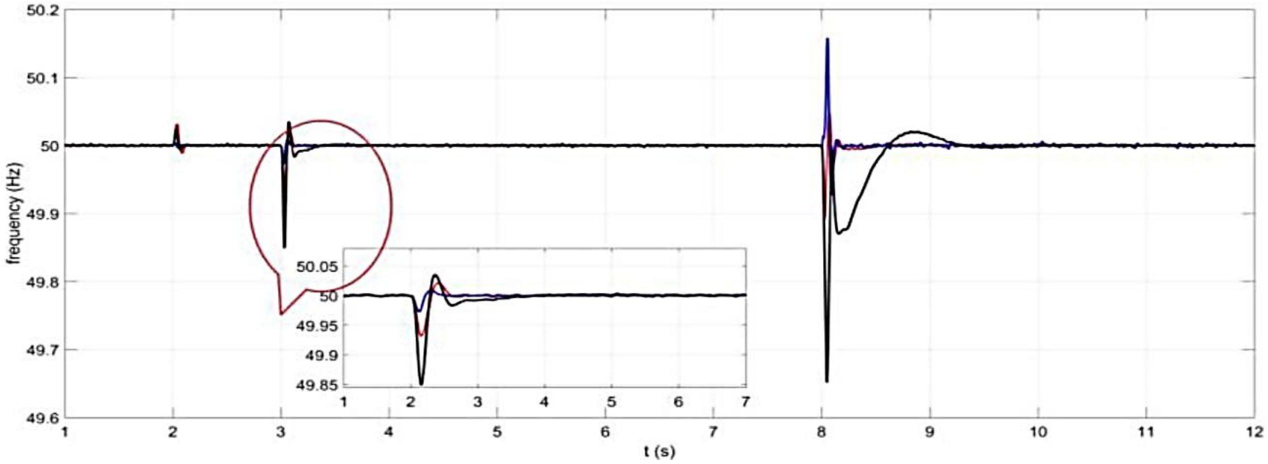

Fig. 6- The frequency of MG in DG's buses

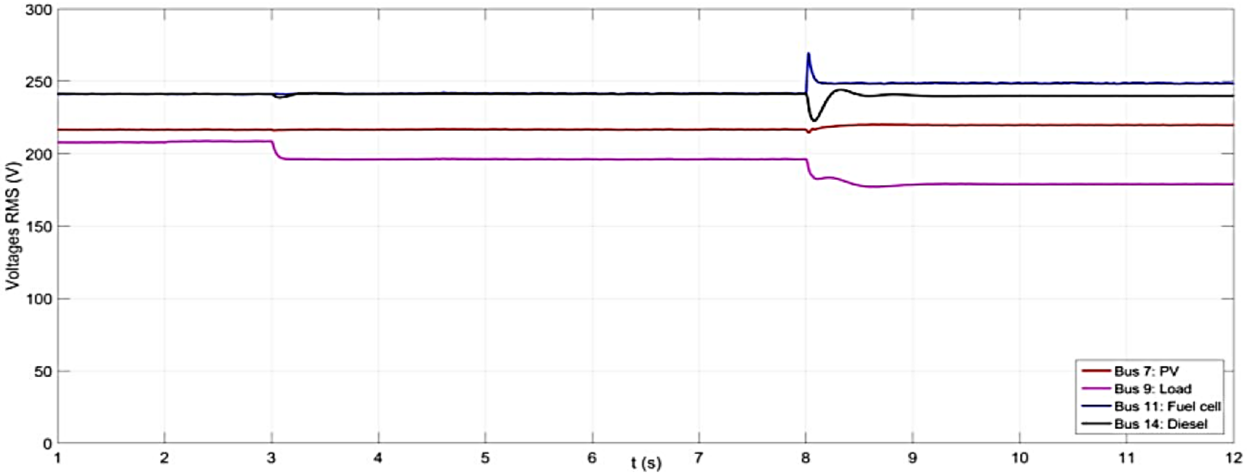

Fig. 7- The voltage of MG in several buses

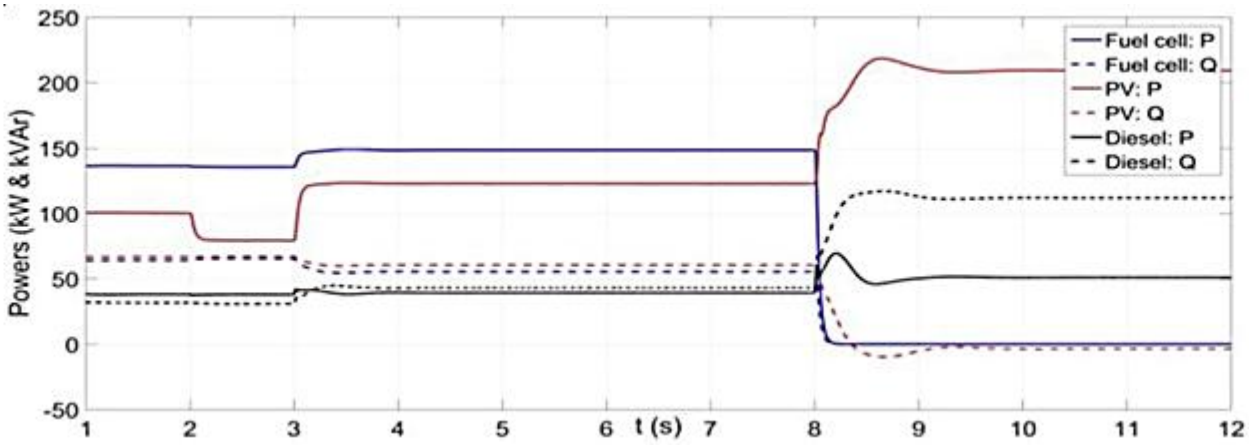

Fig. 8- The powers of DGs in the MG

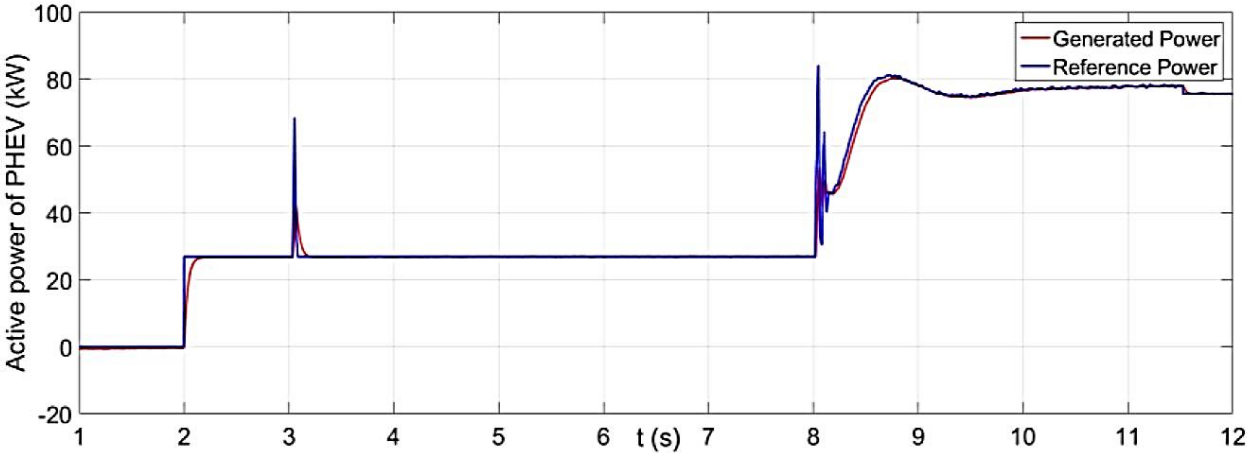

Fig. 9- The PHEVs injected power (V2G)

5. Conclusions

In this paper, a new intelligent droop control for inverter based DG units in the MG has been proposed that can be used for primary voltage and frequency control. ANFIS training has been used for training the controllers. One major contribution of this paper is to share the PHEVs in the MG's voltage and frequency control. Based on the contract between vehicle's owner and the system operator, PHEVs participate in controlling the voltage and frequency by fast injection of active power. Simulation studies show that, the proposed method can do the primary voltage and frequency control, effectively. The steady state error of frequency is negligible and the voltage drop is acceptable. The studied MG consists of both inverter-based and diesel generator. The role of PHEVs is to participate in the primary voltage and frequency control, based on the contract between vehicle's owner and the system operator. It is seen that the role of PHEVs can be prominent, due to their fast power injection capability. Both voltage and frequency in the MG can be controlled through active power injection.

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