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Optimal intelligent control of plug-in fuel cell electric vehicles in smart electric grids

Amin Hajizadeh*[1], Masoud Aliakbar Golkar[2]

[1] Department of Electrical Engineering, University of Shahrood, Shahrood, Iran.
[2] Department of Electrical Engineering Department, K.N.Toosi University of Technology, Tehran, Iran.

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Abstract

In this paper, Plug-in Fuel Cell Electric Vehicle (PFCEV) is considered with dual power sources including Fuel Cell (FC) and battery Energy Storage. In order to respond to a transient power demand, usually battery energy storage device is combined with fuel cell to create a hybrid system with high energy density of fuel cell and the high power density of super capacitor. In order to simulate the PEV model, dynamic state space models of bidirectional DC-DC converter and grid connected voltage source converter are considered to connect the PFCEV to the main grid.
In order to stabilize the DC-link power and distribute the power between dual energy storage sources in PEV during normal and disturbance conditions on the grid voltage, a fuzzy control strategy has been developed. For fine tuning the parameters of fuzzy logic controller, the PSO (particle swarm optimization) algorithm has been used. This controller determines the super capacitor and fuel cell powers that should be generated according to the amount of available energy in DC-link. Moreover, a robust sliding mode control strategy for three phase power electronic converter based on the positive and negative symmetrical components is presented to investigate the voltage disturbance ride-through capability.

1. Introduction

Gridable Electric Vehicles (GEV), such as plug-in hybrid electric vehicles and battery-electric vehicles, have recently become more attractive options over combustion engine-based vehicles, due to the high fuel price and environmental concerns. Plug-in electric vehicles (PEVs) will be the next phase in the evolution of hybrid electric vehicles. Their batteries will be charged by plugging into electric outlets or on-board electricity generation. [1-3].

Batteries, ultra capacitors (UCs), and fuel cells are widely being proposed for electric vehicles (EVs) and plug-in hybrid EVs (PHEVs) as an electric power source or an energy storage unit. Integration of these power sources with power electronic converters provides conditions that the PEV could operate in smart grid with more flexibility [4]. The power flow in V2G can be both

* Corresponding author:
e-mail:aminhajizadeh@shahroodut.ac.ir & Golkar@kntu.ac.ir

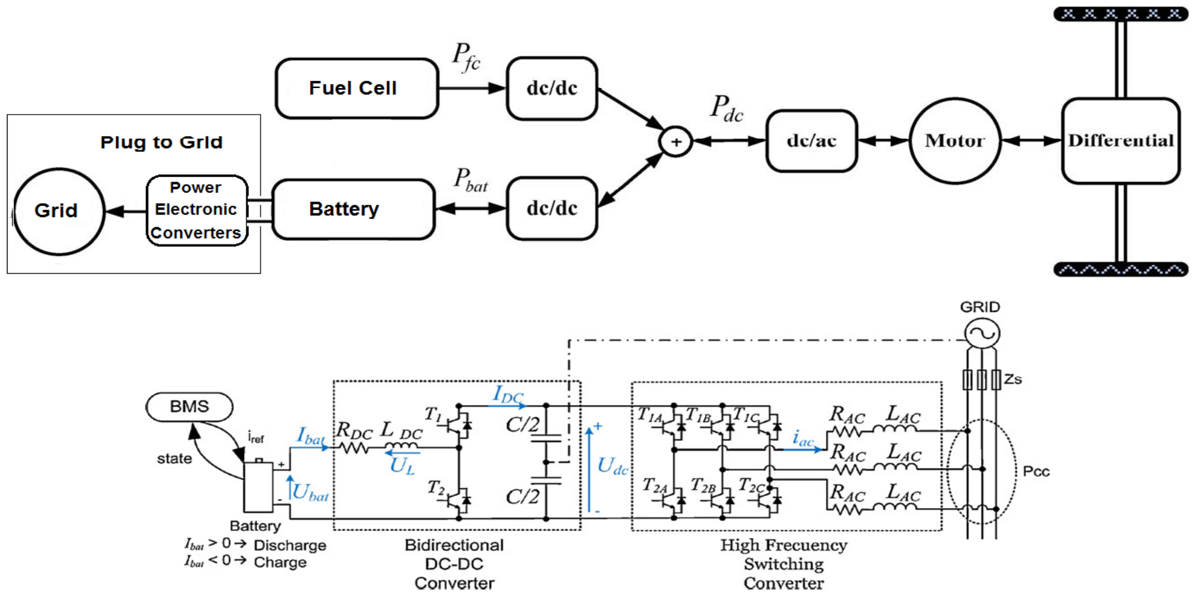

Fig 1. Vehicle topology of Fuel Cell PEV with Power Electronic Converters

unidirectional and bidirectional, though in unidirectional V2G only services such as frequency regulation and delivering power, are provided to the grid. Through V2G, EV owners can potentially generate revenue while charging their cars and at the same time mitigate the negative impacts on the grid from charging. With V2G, an EV can participate in most energy markets, from bulk energy, to spinning reserves and frequency regulation [5-7]. Plug-in Electric Vehicles (PEV) are connected to smart grid via power electronic converters to support the grid. So, it is important that the control strategies are designed to keep the system stable under any disturbance and parameter variations in the electrical distribution system. The grid-connected power electronic converters are highly sensitive to grid disturbances and it is important to emphasize the necessity to reduce the effects of voltage disturbances on their operation. In this chapter, PEV is considered with dual power sources. In order to respond to a transient power demand, usually battery energy storage device is combined with fuel cell. This type of hybrid system uses fuel cell as a high energy density source and battery energy storage as a high power density source as well. For simulation studies, dynamic models of bidirectional DC-DC converter and grid connected voltage source converter are considered to connect the hybrid power sources to the main grid. In order to stabilize the DC-link power and distribute the power between fuel cell and battery energy storage in PEV during normal and disturbance conditions on the grid voltage, a PSO-based fuzzy control strategy has been developed. This controller determines the fuel cell and battery power that should be generated optimally. Moreover, a robust sliding mode control strategy for voltage source converter based on positive and negative symmetrical components is presented to investigate the voltage disturbance ride-through and voltage control capability.

2. Architecture of the plug- in fuel cell elecctric vehicle

The modeling of Plug-in Fuel Cell Electric Vehicle (PFCEV) is an important issue that needs to be carefully addressed. In Fig. 1, overall structure of PEV is shown. Many articles deal with static models that are built up from maps and static relationships between parameters in the model.
These models allow for fast simulation, but they cannot show the oscillations and other dynamic phenomena when switching occurs between different modes of operation. However, a good model should consider both accuracy and simulation time. The components of the models of plug-in fuel cell electric vehicle used in this paper comprise a PEM fuel cell, battery bank, DC/DC and DC/AC converters. The details of modeling of each power sources and power electronic converters can be found in [8-9].

3. Poewr control of plug- in fuel cell electric vehicle

PEV batteries can be utilized as distributed energy storage in order to support the grid. With the bidirectional converter, hybrid fuel cell/energy storage system can behave both as a source or a sink, i.e., the vehicles at the charging station can collectively discharge or charge respectively. The bidirectional converter, interfaced with the PEV energy storage is synchronized with the grid system at point of common coupling (PCC). Power injection to grid from hybrid power sources, is achieved by voltage source inverters. The grid-connected converters are highly sensitive to grid disturbances and it makes to emphasize the necessity to reduce the effects of voltage disturbances on their operations [10]. In spite of the growing number of V2G units, their contribution of power delivered to the utility grid remains small, as compared to the power injected by the large centralized power plants. However, to support the grid in case of disturbances, it will become necessary to keep the V2G units connected to the grid. In the wide range of power quality disturbances, the interest focuses on voltage sags, which can severely affect the performance of the voltage source converter (VSC). A voltage sag is a drop in voltage with duration between one half-cycle and one minute [10], which is in most cases is caused by a short-circuit fault. Therefore, the operation of V2G under voltage sag has not received much attention in the past. However, as the power generated by V2G increases, this behavior stresses the utility grid and could cause power unbalance, which may turn into instability. So, the interaction between V2G and the grid during the voltage sag is very important and it must be considered for designing the proper control strategy. Hence, in this paper a control strategy is proposed for V2G including energy storages under voltage disturbance conditions. During the voltage disturbance in distribution systems, a decrease in voltage magnitude at the grid-connected converter occurs. In this case, the current is controlled to avoid overloading the converter above the limit of the power that V2G can supply to the grid during voltage disturbance. In fact, during voltage disturbance conditions, the power flow control strategy must be designed to stabilize the dc link power and consequently, regulate the dc link voltage. During the voltage disturbance, a decrease in voltage amplitude occurs at the converter terminal. To keep the power supplied to the grid constant, the current should increase; it will be limited by the current controller however, to avoid overloading of the converter. This will thus limit the power that the V2G can supply to the grid during voltage disturbance, resulting in the DC-link voltage to increase. To avoid a too high DC-link voltage, the power balance between inverter power and V2G power must be satisfied. According to three operation modes for V2G, the DC-link voltage is given by three different state equations:

Discharging mode:

$$C_{dc} v_{dc} \frac{dv_{dc}}{dt} = P_{V2G} - P_{inv}$$
$$P_{V2G}(k) = P_{Batt}(k) + P_{FC}(k) \quad (1)$$

Charging mode:

$$C_{dc} v_{dc} \frac{dv_{dc}}{dt} = P_{inv} - P_{V2G}$$
$$P_{V2G}(k) = P_{Batt}(k) + P_{FC}(k) \quad (2)$$

Disconnected Mode:

$$C_{dc} v_{dc} \frac{dv_{dc}}{dt} = P_{V2G} - P_{load}$$
$$P_{V2G}(k) = P_{Batt}(k) + P_{FC}(k) \quad (3)$$

In this mode, the V2G is not connected to grid and it could be used for supplying electrical motor to propel the vehicle. According to the above mentioned equations, P_{V2G}, P_{inv}, P_{load} , P_{Batt}, P_{FC}, C_{dc} and v_{dc} are V2G power supplied to the DC-link, inverter power (grid power), electrical load power, battery power, fuel cell power, DC-link capacitor and voltage, respectively. During the voltage disturbance, the reference power of inverter is determined by the maximum power that can be supplied to the grid. So, the V2G power must be decreased to avoid a too high DC-link voltage. Hence, the power flow control of PFCEV is very important task and it changes the operating point of the system during voltage disturbance. To improve the performance of the power flow control strategy, the optimal fuzzy control strategy shown in Fig. 2 is proposed. In this control structure, the fuel cell power (P_{FC}) and battery power (P_{Batt}) are determined according to the demand power (P_{load}), the output current of inverter ($I_{inv}(k)$), the error voltage (voltage difference between desired voltage and bus voltage) $V_{dc}(k)$ and its derivative, the state of charge of the battery (SOC) and the fuel cell and battery power in one time step back ($P_{FC}(k-1)$, $P_{Batt}(k-1)$). To generate the fuel cell power optimally, the efficiency maps of the fuel cell is used.

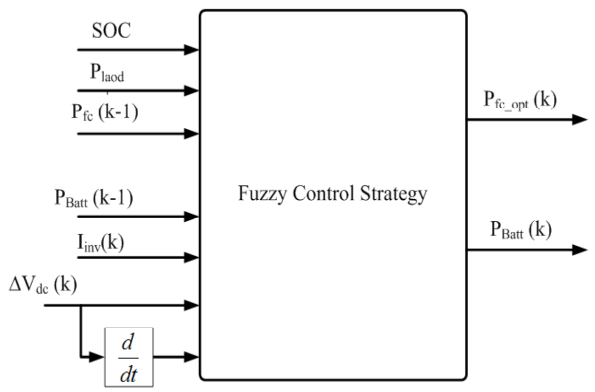

Fig 2. Power Flow control structure

As shown in Fig. 3, the maximum efficiency of the fuel cell is at the level power between 20kW and 30kW. Moreover, the maximum efficiency of the battery during the charge and discharge cycles is around the state of charge of 75% [4]. In fact, the output current of inverter and the error voltage between desired voltage and bus voltage ($V_{dc}(k)$) and its derivative are very important during the decision process to stabilize the dc bus voltage during the voltage disturbance. Also, the battery power and fuel cell power in one step ago ($P_{FC}(k-1)$, $P_{Batt}(k-1)$) help the fuzzy controller to decide the exact time to start charging or discharging the battery. Moreover, in order to operate the fuel cell stack at an optimal fuel utilization point, the fuel cell controller is to maintain an optimal hydrogen utilization, $U_{f,opt}$, around 85% [11]. During the voltage disturbances, the power flow control strategy must be designed to manage the power between the dual power sources and the utility grid.

It is proven that there is a direct proportionality between the maximum current of the voltage source converter and the value of the actual input power to dc bus [9]. In other words, if the input power to dc bus is lowered by the ratio K, the maximum value of the current will also be lowered by the same ratio. To calculate the required current rating of the voltage source converter switches to ride-through voltage disturbances at the grid, the maximum current has been calculated [9].

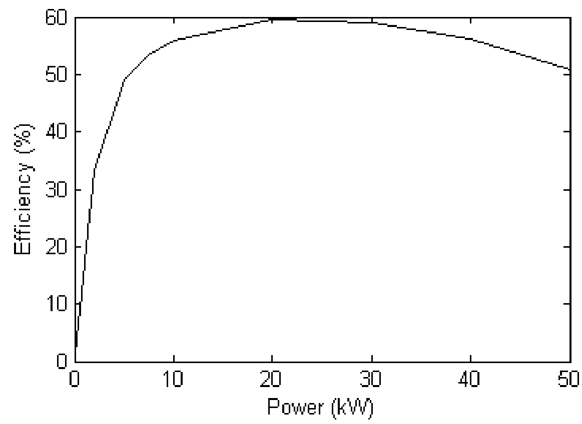

Fig 3. Efficiency map of fuel cell stack

Fuzzy controller is used to decide the operating point of the fuel cell stack. It is necessary to determine the fuel cell stack optimal power to assist the energy storage in charge or discharge modes. It follows the idea of load leveling, where the energy storage is used to provide assisting or generating, while operating the fuel cell at an optimum. The controller determines the controller output based on the inputs using a list of if-then statements called rules. The if-part of the rules refers to adjectives that describe regions (fuzzy sets) of the input variables. A particular input value belongs to these regions to a certain degree, so it is represented by the degree of membership. To obtain the output of the controller, the degrees of membership of the if-parts of all rules are evaluated, and the then-parts of all rules are averaged and weighted by these degrees of membership. All membership functions for inputs and outputs of fuzzy controller have been chosen as Gaussian type. Furthermore, for implementation of controller the Mamdani structure is used. The core of the rule set of the fuzzy controller is illustrated as follows:

(*1*) *Energy storage Charge Mode*

Rule 1: if P_{load} is Low and SOC is Low and $P_{Batt}(k-1)$ is Negative High and $P_{FC}(k-1)$ is Low then $P_{FC}(k)$ is Medium.

Rule 2: if P_{load} is Medium and SOC is Low and P_{Batt} *(k-1)* is Negative Medium and $P_{FC}(k-1)$ is Medium then $P_{FC}(k)$ High.

Rule 3: if P_{load} is Medium and SOC is Low and

P_{Batt} *(k-1)* is Negative Low and $P_{FC}(k-1)$ is Medium then $P_{FC}(k)$ is High.

(2) Hybrid Mode

Rule 4: if P_{load} is Medium and SOC is High and $P_{Batt}(k-1)$ is Low and $P_{FC}(k-1)$ is Low then $P_{FC}(k)$ is Medium.

Rule 5: if P_{load} is Medium and SOC is High and P_{Batt} *(k-1)* is Medium and $P_{FC}(k-1)$ is Medium then $P_{FC}(k)$ is Medium.

Rule 6: if P_{load} is Medium and SOC is High and P_{Batt} *(k-1)* is Medium and $P_{FC}(k-1)$ is Medium then $P_{FC}(k)$ is Low.

Rule 7: if P_{load} is High and SOC is High and P_{Batt} *(k-1)* is Low and $P_{FC}(k-1)$ is Medium then $P_{FC}(k)$ is High.

Rule 8: if P_{load} is High and SOC is High and P_{Batt} *(k-1)* is Medium and $P_{FC}(k-1)$ is Low then $P_{FC}(k)$ is Medium.

Rule 9: if P_{load} is High and SOC is High and P_{Batt} *(k-1)* is Medium and $P_{FC}(k-1)$ is High then $P_{FC}(k)$ is Medium.

Rule 10: if P_{load} is High and SOC is High and P_{Batt} *(k-1)* is High and $P_{FC}(k-1)$ is Medium then $P_{FC}(k)$ is Low.

Rule 11: if P_{load} is High and SOC is Low and P_{Batt} *(k-1)* is Low and $P_{FC}(k-1)$ is Medium then $P_{FC}(k)$ is High.

(3) Energy storage Operation Mode

Rule 12: if P_{load} is Low and SOC is High then $P_{FC}(k)$ is Zero.

(4) Voltage Disturbance Mode

Rule 13: if $\Delta V_{dc}(K)$ is high and the derivative of $\Delta V_{dc}(K)$ is high and $I_{inv}(k)$ is high then $P_{FC}(k) = P_{FC}(k-1)$ and the $P_{ES}(k)$ is negative high.

Rule 15: if $\Delta V_{dc}(K)$ is high and the derivative of $\Delta V_{dc}(K)$ is high and $I_{inv}(k)$ is medium then $P_{FC}(k) = P_{FC}(k-1)$ and the $P_{ES}(k)$ is negative medium.

Rule 16: if $\Delta V_{dc}(K)$ is high the derivative of $\Delta V_{dc}(K)$ is is zero and $I_{inv}(k)$ is low then $P_{FC}(k) = P_{FC}(k-1)$ and the $P_{ES}(k) = P_{ES}(k-1)$.

In this condition the energy storage power command is negative and the lower power transferred to dc bus and to the grid consequently to stabilize the dc voltage.
In order to design the optimal fuzzy controller, the PSO algorithms are applied to search globally optimal parameters of the fuzzy logic. This process has been explained in next section.

$$E(k) = \sum_{k=1}^{N-1} \begin{matrix} w_1\left(P_{fc}(k) - P_{fc-opt}\right)^2 + w_2\left(SOC(k) - SOC_{opt}\right)^2 \\ +w_3\left(U_f(k) - U_{f-opt}\right)^2 \end{matrix} \qquad (4)$$

where N is the duration of the power demand and w_1, w_2 and w_3 are the weighting coefficients representing the relative importance of the objectives and they must satisfy the equation.

$$w_1+w_2+w_3=1 \qquad (5)$$

Particle swarm optimization (PSO) is a population based stochastic optimization technique inspired by social behavior of bird flocking or fish schooling [13]. The system is initialized with a population of random solutions and searches for optima by updating generations. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles and each individual adjusts its flying according to its own flying experience and its companion's flying experience. Each particle keeps track of its coordinates in the problem space which are associated with the best solution (fitness) it has achieved so far. This value is called 'pbest'. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called 'gbest'. Much work has been done on the analysis of fuzzy control rules and membership function parameters [14]. The PSO algorithms were used to get the optimal values and parameters of our FLC. The structure of proposed algorithm is shown in Fig. 4.
In particular, particle i remember the best position it has visited so far, referred to as *pbesti*, and the best position by its neighbors. There are two versions for defining the neighbors' best position, namely *lbest* and *gbest*. In the local version, each particle keeps track of the best position *lbest* attained by the particles within its topological neighborhood. For the global version, the best position *gbest* is determined by any particle in the entire swarm. Hence, the *gbest* model is a special case of the *lbest* model. The PSO is an

evolutionary algorithm. At each iteration, particle i adjusts its velocity v_{ij} and position p_{ij} through each dimension j by referring to the personal best position ($pbest_{ij}$) and the swarm's best position ($gbest_j$, if the global version is adopted) using Eqs. (6) and (7) as follows:

$$v_{ij} = k\left(v_{ij} + c_1 r_1 \left(pbest_{ij} - p_{ij}\right)\right) \qquad (6)$$

and

$$p_{ij} = p_{ij} + v_{ij} \qquad (7)$$

where c_1 and c_2 are the acceleration constants, r_1 and r_2 are random real numbers drawn from $U(0,1)$, and k is the constriction factor. Clerc and Kennedy [13] have pointed out that the use of a constriction factor is needed to ensure convergence of the PSO, and it is determined by:

$$k = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|} \qquad (8)$$

where $\varphi = c_1 + c_2 > 4$. Typically, φ is set to 4.1, and thus k is 0.729.

As such, the particle flies through candidate solutions toward $pbest_i$ and $gbest$ in a navigated way while still could explore new potential solutions by the random multipliers to escape from local optima. The PSO algorithm is terminated with a maximal number of iterations or the best particle position of the entire swarm cannot be improved further after a sufficiently large number of iterations.

4. Robust sliding mode control strategy for voltage source converter based on positive and negative symmetrical components.

Control of grid connected voltage source converter (VSC) is an important problem during voltage disturbances like voltage sag. A voltage sag is a reduction in the RMS voltage in the range from 0.1 to 0.9 p.u. of the nominal voltage for a duration greater than half cycle and less than one minute. The drawback of using VSC is its sensitivity to voltage disturbances. For a VSC, a sudden decrease in grid voltage normally causes an increase in current, as the control attempts at maintaining the power to the DC-link constant. Moreover, most faults are unbalanced and result in unbalanced voltage sag, which produce undesirable power oscillations of low order frequencies in current harmonics and poor DC-link voltage regulation. Ultimately, this can also lead to tripping of the converter due to DC overvoltage. The VSC is connected to the grid via a filter inductor. The dq-components of currents and voltages are then used along with the reference current signals. The VSC controller is required to have two main functions: Current control and DC-link voltage regulation. A comparison between different types of current controllers for shunt connected VSC, has proved that Dual Vector Current Controller (DVCC) is capable of providing sinusoidal grid currents and regulated DC-link voltage during unbalanced faults. The current controller used in this paper consists of two sliding model controllers that control the positive and negative sequence current separately and are implemented in two different rotating coordinate systems [9]. A simplified scheme for the DVCC is shown in Fig. 5. The VSC is connected to the grid via filter inductors. The three phase grid currents and voltages are sampled and transformed into its positive and negative sequence components. The positive and negative sequence of *dq*-components are then used along with the reference current signals in the DVCC to produce the reference voltage signals for the PWM regulator. According to the proposed control strategy in [9], the purpose of the current controller is to synthesize a voltage correction vector so that the current error vector can be kept to a minimum value. The details of proposed controller has been introduced in [9].

5. Simulation results

In order to show the effectiveness of the proposed control strategy, the simulation model of the proposed hybrid V2G system has been built in Matlab/Simulink environment. The parameters of the hybrid fuel cell/battery energy storage system in this study are given in [9,12]. The battery operates as a buffer of energy to meet load demand that cannot be met by the fuel cell energy source, particularly during transient or disturbances periods. In this case study, the output power of the fuel cell is limited to 50 kW and the battery bank is capable of sustaining the extra load of 20 kW. Also, it is supposed that the initial state of charge for battery is 0.7. The system was tested under two different operating conditions to investigate its power flow control during normal and faulty conditions.

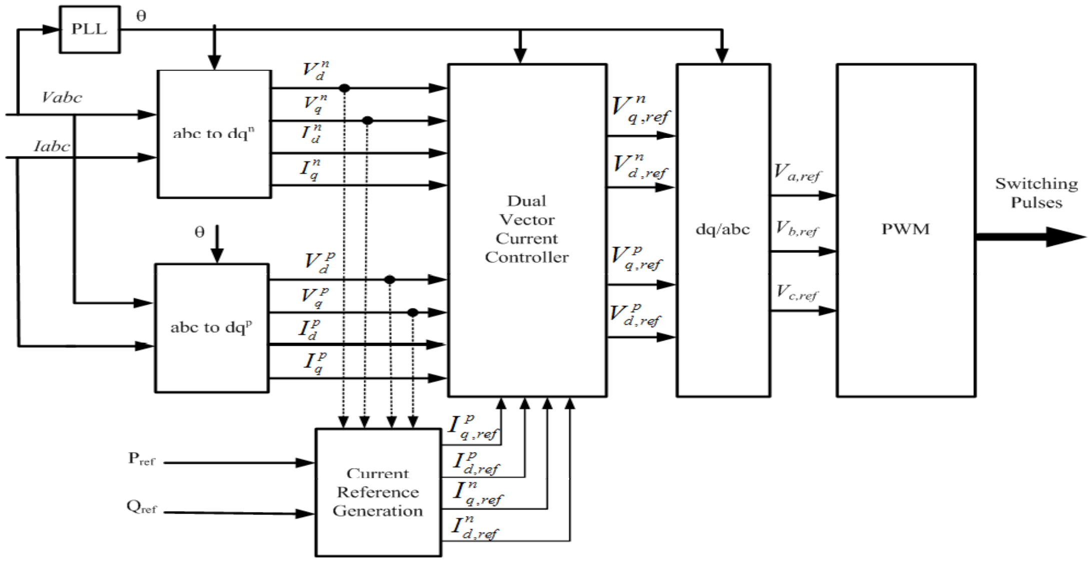

Fig 5. Block Diagram of Robust Dual Vector Current Controller.

A. Grid Support during Normal Conditions

A certain amount of power may be scheduled to be delivered to a load center from the utility grid with the rest to be supplied by the plug-in fuel cell electric vehicle. Here, it is supposed that only active power is injected to grid by PFCEV. Fig. 6 shows the required power form V2G that could be determined from Electric Distribution Company in smart grid environment for special time duration.

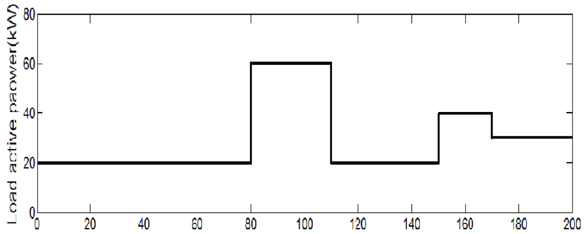

Fig 6. required power form V2G

Fig. 7 depicts the fuel cell characteristics during the change in the requested power. Moreover,, the variations of battery energy storage is shown in Fig. 8. As illustrated, when the reference of active power changes, the battery power also varies to deliver part of power during transient to stabilize DC-link power. Moreover, due to slow dynamics of fuel cell, its generated power changes slowly.

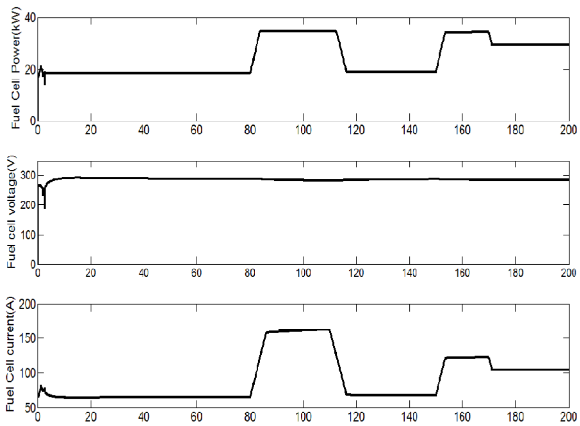

Fig 7. fuel cell characteristics during the change in the requested power

B. Dynamic Behavior of PFCEV during Voltage disturbance

For the investigated system, simulations have been done with unbalanced voltage sag (type C) with the magnitude between 0.3 and 0.9 p.u. Maximum grid current and peak- to-peak DC voltage ripple during the sag are shown for sag type C in Figs. 9 and 10. In order to ride through sag with minimum retained voltage of 30%, the converter switches should be able to carry a maximum current of 3.65 p.u. The maximum DC voltage ripple is ±0.25% around the nominal value for sag magnitudes below 30%. Moreover, for the evaluation of proposed control strategy, simulations have been run with unbalanced voltage sag (type C) with magnitude 40%. The sag starts at 0.3sec and ends at 0.4sec. The DC-link voltage is shown in Fig. 10. The grid currents increase to above 2 p.u, and DC voltage shows a variation during the transients at the beginning and end of the sag. However, the ripple during the transient is not bigger than 10% peak-to-peak and is quite quickly damped to almost zero. As shown in Fig. 11, the generated power of the hybrid power sources decreases during voltage disturbance to increase the voltage sag ride-through capability. In fact, during the voltage sag, the current controllers limit the output current to avoid the overloading of the converter. As a result, the average and instantaneous active power that converter supplies to the grid deceases (Fig. 11), resulting in an increase in dc link voltage (Fig. 12). The grid converter now controls the power (with its set point determined by the maximum current).

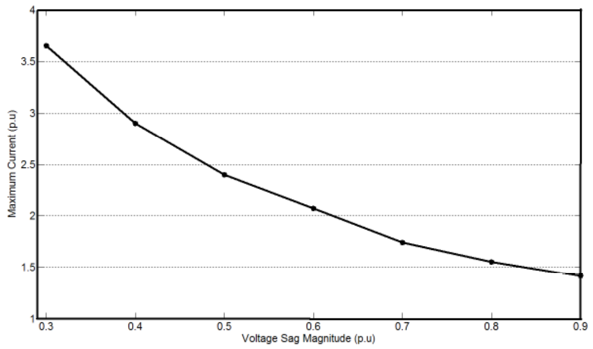

Fig 9. Maximum grid current in p.u for voltage sag type C with magnitude between 0.3 and 0.9.

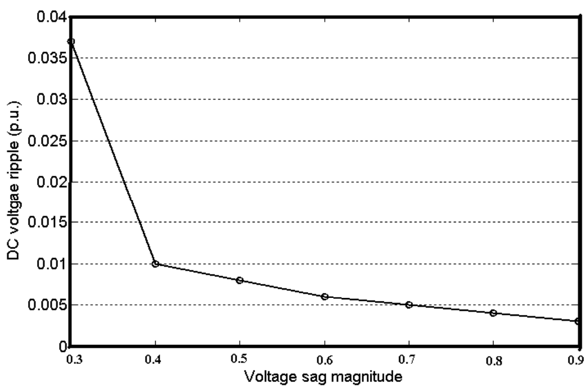

Fig 10. DC-link voltage ripples in p.u for voltage sag type C with magnitude between 0.3 and 0.9.

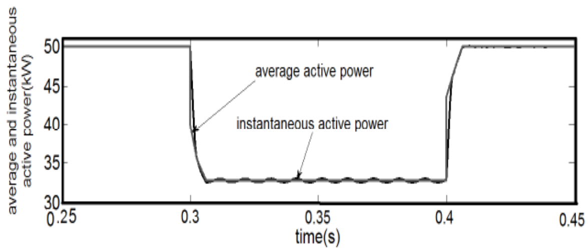

Fig 11. Generated average and instantaneous active power by FCPEV during voltage sag

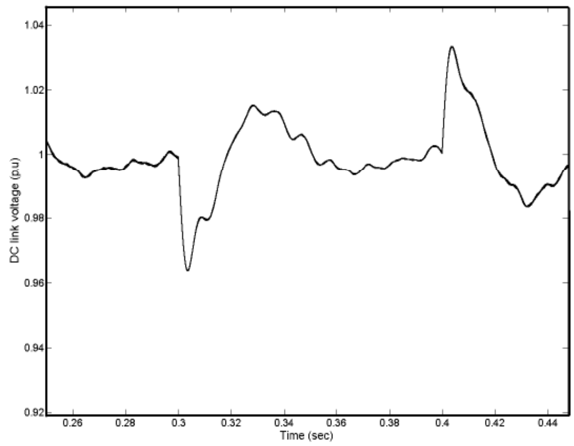

Fig 12. DC-link voltage control during 40 % voltage sag type C (p.u).

In these conditions, to stabilize the DC-link voltage, the fuzzy controller manages the power flow between battery and fuel cell, resulting the reference power of the battery bank changes for decreasing the input power to dc bus during voltage disturbances, and fuzzy control strategy switches the energy storage bank to the charging mode and energy storage's state of charge (Fig. 13) goes high and remain constant on a new value. On the other hand, during the voltage sag,

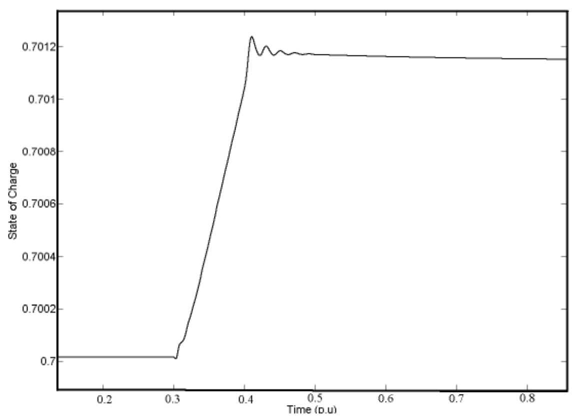

Fig 13. Energy storage's state of charge during voltage sag.

the battery improves the performance of V2G. In this condition, the proposed power flow control strategy finds the suitable operating point for the fuel cell and battery energy sources.

6. CONCLUSION

In this paper, PFCEV is considered with dual energy storage sources. For simulation studies, dynamic models of bidirectional DC-DC converter and grid connected voltage source converter are considered to connect the hybrid power sources to the main grid.

In order to stabilize the DC-link power and dis tribute the power between dual energy storage sources in PEV during normal and disturbance conditions on the grid voltage, a PSO based fuzzy control strategy has been developed. This controller determines the super capacitor power that should be generated according to the amount of available energy in DC-link. Moreover, a robust sliding mode control strategy for voltage source converter based on positive and negative symmetrical components is presented to investigate the voltage disturbance ride-through and voltage control capability.

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