Modeling and Simulation of PHEV as a Virtual UPQC Based on Vehicle to Grid Technology

M. Aryanezhad¹, M. Joorabian², E. Ostadaghaee³

Abstract – Power electronic-based FACTS devices like Unified Power Quality Conditioner (UPQC) can fulfill multiple power quality control objectives such as needs of reactive power compensation, voltage flicker and harmonics current compensation. Although the main disadvantage of UPQCs are their excessive price. Therefore UPQCs are not widely used. In this paper a method proposed to analyze the reactive and active power transaction capabilities of a practical vehicle battery in the Plug-in Hybrid Electric Vehicles (PHEV) in a Vehicles to Grids (V2G) mode of operation, which gives a low-cost solution for designing a virtual UPQC using PHEV charging station.

A third order dynamic battery model is used to represent the PHEV and substitute to dc link of UPQC. Simulations have been executed in MATLAB SIMULINK and demonstrated that PHEVs have able to work as a virtual UPQC to improve power quality.

Keywords: V2G, UPQC, PHEV, Battery Model, Smart Grid

Nomenclature

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<td>PHEV</td>
<td>Plug-in hybrid electric vehicle</td>
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<td>UPQC</td>
<td>Unified power quality conditioner</td>
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<td>V2G</td>
<td>Vehicle to grid</td>
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<td>FACTS</td>
<td>Flexible AC transmission system</td>
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<td>STATCOM</td>
<td>Static synchronous compensator</td>
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<td>HVDC</td>
<td>High voltage direct current</td>
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<td>SOC</td>
<td>State of charge</td>
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<td>DOC</td>
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<td>se</td>
<td>Series compensator</td>
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<td>Shunt compensator</td>
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<td>$V_d$</td>
<td>De voltage of battery</td>
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<td>$\theta$</td>
<td>Electrolyte temperature</td>
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<td>$Z_m$</td>
<td>Impedance of main branch of PHEV</td>
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<td>$Q_e$</td>
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<td>$V_e$</td>
<td>Lead-acid battery hysteresis voltage</td>
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<tr>
<td>$\alpha\beta$</td>
<td>Clarke transformation</td>
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<tr>
<td>$p, q$</td>
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I. Introduction

Along with the increasing of concerns about the pollutions produced by fossil fuel engines to forcing the vehicle market to discover new alternatives to decrease the fossil fuel usage. Different electric vehicle and hybrid electric vehicles are viable alternatives to displace for common fleet of fossil fuel driven vehicles.

Plug-in Hybrid Electric Vehicles (PHEV) are suitably to be a strong alternative to the current vehicle due to promotion in battery and hybrid electric power technologies, meet up with the financial, energy security necessity, concerns about environmental and the cost of fossil fuel [1],[2], [25]-[30].

Therefore, in recent years, the number of PHEVs entering the market have been increasing very quickly. These vehicles could helped in vehicle-to-grid (V2G) power transactions in the proposed smart grid in the near future. A survey showed that most US population drive are parked more than 95% of the day [3], their expectable nature can be provide successfully in V2G transactions.

In V2G mode of operations, the PHEV fleet can give many grid services, such as voltage regulation management [3],[4], load leveling [5], external storage for renewable energies resources [6], and generating revenue with transaction power at different times according to variable price curves [7], [8].

Another important service of the PHEV is reactive power support, which has not been studied previously.

The ability of reactive power compensation of a vehicle battery has been deliberated in [9], where the inverter is responsible for reactive power compensation. The dc-dc converter charges the battery based on the constant-current and constant-voltage algorithm.

In the presented algorithm in [10], the inverter is connected directly to the battery instead of dc-dc converter. The capability of reactive power of a single...
vehicle has been utilized in a residential level power system.

PHEV with a huge capacity battery are able to compensate reactive power to utility grid has been reported in [11]. Another study of using PHEV as STATCOM has been demonstrated that PHEV battery have the capability to serve as STATCOM [12]. Effective economic way of electricity buying and selling from PHEV according to variable price curves were reported in [7,8]. These preceding studies have not dealt with the dynamic behavior of PHEV battery along with the series and shunt compensating strategies as UPQC does.

In this paper a comprehensive way of utilizing PHEV batteries and their bidirectional charger in a charging station as virtual UPQC has been demonstrated in V2G mode of operation. A smart park model with dynamic behavior of battery has been developed. PHEVs are suitable to be a strong alternative to the current vehicle due to advancement in battery and hybrid electric power technologies [13],[14].

PHEVs can be charged from residential electric connection as well as from an ubiquitous power charging station. PHEVs give chance to design its bi-directional charger as UPQC converters. PHEVs suggest occasion of storing electric wind energy and photovoltaic energy at times of excess generation and use as an ubiquitous power grid whenever needs for improvement of power stability and quality of those resources. Fig. 1 shows an ubiquitous power grid based on PHEV in a V2G.

![Fig. 1. An ubiquitous power grid based on PHEV in a V2G](image)

Power system parameters which determine the transmittable power can be controlled with any combination in real time using UPQC. It can be describe as a generalized power flow controller which can maintain certain amount of real and reactive power necessary for normal and temporary system operating conditions. Compare to other FACTs devices such as static compensator (STATCOM), thyristor controlled series capacitor (TCSC), it becomes evident that UPFC is unique in its capability to control both real and reactive power [15]. A basic Configuration of UPQC is given in Fig. 2.

Although UPQC is one of the most versatile FACTs controller developed so far, yet it is not widely used for power quality improvement due to its cost.

On an average the cost of UPQC devices per kVA is twice than STATCOM [16]. On the other hand the most expensive components for the constitution of FACTS or HVDC devices are the capacitors [17]. Therefore PHEV is a good substitution for capacitors of these devices.

Harmonics is one of the main problem that could hinder power transmission and losses whether sometimes could failures in operation of electronic apparatuses.

Therefore, the power quality delivered to the customers is an object of great worry and it is obligatory to solve the harmonic problems caused by those equipments already installed [18], [31].

This paper researches the feasibility of utilizing PHEVs as UPQC through its bidirectional converter using pq theory for control. Bidirectional converter of PHEV have the capability run in different mode of operation according to need, which has been reported in [19].

The rest of this paper is arranged as follows: Section II provides the dynamic model of PHEV; Section III represents the Controller Design and reference signals generation and Section IV contains the test system design and simulation results. Finally, Section V is included by future work and conclusions.

II. Dynamic PHEV Model

Battery charging of PHEVs requires having an electronic interface to connect the power grid. Together with the battery state of charge (SOC) and dynamic reaction of electrolyte temperature, the impact of electronic charger is considered to model of the system [20]. To evaluate the battery of PHEVs, considering the range of driving 40 miles/day, which means the capacity of a PHEV battery will be 12 kWh [21], [22].

To develop an appropriate model of PHEV, a dynamic model of a rechargeable battery [23] has been chosen where the elements of battery are variable, as they depend on electrolyte temperature as well as on the state of charge (SOC). Fig. 3, represented the battery equivalent, where \( \theta \) is the electrolyte temperature and...
SOC is the state of charge of battery. $I_m$ is an essential part of the total current (I) as shown in Fig. 3.

![Image of battery equivalent network](image)

Fig. 3. Battery equivalent taking into account a parasitic reaction[23]

Another part of the dc current pass through the parasitic branch is called $I_p$. Parasitic reaction is an uninterrupted process, that pull the current but does not involved at main reaction. The power scattered in real part of impedances $Z_m$ and $Z_0$ is changed into the heat.

With charging, the impedance of main reaction branch increased.

This result cause the terminal voltage of parasitic branch rise as well as the current $I_p$. At a full state of battery, the impedance of the main reaction branch access to infinite [23], [24].

![Image of equivalent electric network](image)

Fig. 4. Equivalent electric network used for the third-order battery model [23]

This battery model can be depicted as a RLC network as in Fig. 4 and the number of R-L-C block can be kept limited as the specific speed of development of electric quantities evolve very rapidly for PHEVs [23].

Battery dynamic modeling based on third order is designed regarding current, electrolyte temperature and state of charge (SOC).

The dynamic equations third order battery model are [23]:

\[
\dot{\theta} = -\frac{1}{C_\theta} \left[ \beta_e \theta - \frac{Q_\theta}{R_\theta} \right] \tag{1}
\]

\[
\dot{q_e} = \frac{I_{dc}}{T_s} \tag{2}
\]

\[
I_m = \frac{I_{dc} - I_m}{I_m} \tag{3}
\]

\[
V_{dc} = E_m - R_0 I_{dc} - V_p(\theta, q_e, I_m) + V_p e^{-Beq} \tag{4}
\]

where $V_p$ represents the hysteresis phenomenon for the Lead-Acid battery during charge and discharge cycles.

When battery is charging, the exponential voltage increases and no matter the SOC of the battery. When the battery is discharging, the exponential voltage part decrease quickly.

$V_p$ depends on the sign of $I_m$ as follows:

\[
V_p(\theta, q_e, I_m) = \begin{cases} 
K_p q_e + \frac{R_p I_m}{SOC} & \text{if } I_m < 0 \\
K_p q_e + \frac{R_p I_m}{SOC} & \text{if } I_m > 0 
\end{cases} \tag{5}
\]

$E_m$, $R_0$ are obtained from below equations:

\[
R_0 = R_{00} \left[ 1 + A_0 (1 - SOC) \right] \tag{6}
\]

\[
R_0 = -R_{10} \ln(\text{DOC}) \tag{7}
\]

\[
R_2 = R_{20} e^{A21(1 - SOC)} \tag{8}
\]

\[
E_m = E_{m0} - K_e (1 - SOC)(\theta + 273) \tag{9}
\]

$E_{m0}$, $K_e$, $R_{00}$ and $A_1$, are constant.

The state of charge and depth of charge (DOC) can be obtained as:

\[
\text{DOC} = 1 - \frac{Q_d}{C(I_{avg}, \theta)} \tag{10}
\]

\[
SOC = \frac{Q_m - Q_e}{Q_m} = 1 - q_e \tag{11}
\]

where:

- $C_\theta$: battery thermal capacity
- $P$: power of battery
- $R_\theta$: resistance of thermal
- $Q_\theta$: ambient temperature
- $I^*: reference current$
- $x_e$: Thevenin equivalent reactance
- $\beta_e$: exponential capacity coefficient
- $Q_e$: extracted capacity in (Ah)
- $Q_m$: rated battery capacity in (Ah)
- $K_e$, $E_{m0}$, $K_e$ and $A_1$, are constant.[23].

The current of the parasitic branch can be express as:

\[
I_p = V_p G_p e^{\left[ \frac{V_p}{V_m} + A_p \left( 1 - \frac{\theta}{\theta_f} \right) \right]} \tag{12}
\]
The computation of $R_p$ gives the heat produce by the parasitic reaction by means of Joule law:

$$P_s = R_p I_p^2$$  \hspace{1cm} (13)

Therefore proposed UPQC model can be represented by Fig. 5. The battery model as shown in Fig.4 substituted to capacitor of UPQC. The DC link of UPQCs is an important part of them to balance the power transaction between series and shunt compensators. So, this needs a good strategy for control of voltage of PHEV in a constant value in all operation modes. Generated suitable reference signals for PWM of inverters could make the constant voltage of PHEV.

![Fig. 5. Virtual UPQC modeling based on PHEV](image)

To examine the P-Q capability of PHEV battery a research have been carried out [12] as shown in Fig. 6, where the P-Q capability of a realistic battery vary within ±138 kw and ±138 kVA respectively.

III. Controller Design

In order to develop a controller, UPQC have been realized as a combination of series and shunt converter based FACTS device with DC voltage $V_{dc}$ in common.

Therefore we have two different converter to control UPQC. In both case pq theory is used as the base control theory and then shunt converter have been controlled by controlling current through a hysteresis current controller to get the switching signal for the converter. And series converter has been controller with a simple PWM voltage controller with an additional unwanted high order harmonics voltage $V_f$.

![Fig. 6. Ideal and actual P-Q capability curves of the 307 V and 9.2 kWh battery](image)

The p-q theory is used for designing the controller without considering the neutral wire.

This theory consists of clark transformation of the three phase voltages and currents in the a-b-c coordinates to $\alpha$-$\beta$.

Equations for currents and voltages in $\alpha$-$\beta$ coordinates can be express as [18]:

$$\begin{bmatrix} I_{\alpha} \\ I_{\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} \\ \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{p} \\ I_{q} \end{bmatrix}$$  \hspace{1cm} (14)

$$\begin{bmatrix} V_{\alpha} \\ V_{\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} \\ \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{p} \\ V_{q} \end{bmatrix}$$  \hspace{1cm} (15)

also, the instantaneous real and reactive power are:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_{\alpha} & V_{\beta} \\ -V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} I_{\alpha} \\ I_{\beta} \end{bmatrix}$$  \hspace{1cm} (16)

Therefore, the reference current should be obtained from equation as following:

$$\begin{bmatrix} I_{\alpha}^{ref} \\ I_{\beta}^{ref} \end{bmatrix} = \frac{1}{V_{\alpha}^2 + V_{\beta}^2} \begin{bmatrix} V_{\alpha} & -V_{\beta} \\ V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}$$  \hspace{1cm} (17)

Average and oscillatory part of real and reactive power can be obtained by using low pass filter:

$$p = \bar{p} + \bar{p}$$  \hspace{1cm} (18)

$$q = \bar{q} + \bar{q}$$  \hspace{1cm} (19)
A controller has been developed based on p-q theory. The instantaneous value of active and reactive power have been calculated at Fig. 7.

The proposed UPQC based on PHEV is shown in Fig. 8. When the load is nonlinear, the active and reactive powers can be define as the combination of average and oscillating components.

The undesirable oscillating active and reactive power are produced by harmonic components in load current. The $\alpha\beta$ reference currents can be calculated for these oscillating power.

After that, the Clarke inverse transformation, is used to measure the amount of currents to be injected by the active filter to compensate for these harmonic components in the load.

Fig. 9 and Fig. 10 shows how appropriate reference signal generated for inject to the PWM inverter of shunt and series respectively.

Fig. 7. P-Q generation in the controller

Fig. 8. PHEV modeling as a virtual UPQC
IV. Simulation Results

A line load test system is introduced here to validate the proposed UPQC model.

The test system operates at 230 kV with two thevenin impedance sources connected via transmission lines and a T-tap which is terminated with a Δ-Υ transformer and rated at 230 kV/25 kV as shown in Fig. 11.

The Υ-Υ connected shunt transformer of UPQC rated at 100 MVA, 230kV/21kV and the series transformer is Υ-Δ connected rated at 100 MVA and 92kV/21kV. The source, load and compensating current from virtual UPQC are shown in Figs. 12.

The reactive power transaction between virtual UPQC and bus7 is shown in Fig. 13 and compared with PHEV, where PHEV worked as a virtual UPQC. Simulations have been executed in MATLAB SIMULINK and demonstrated that PHEVs have the ability to work as a virtual UPQC to improve power quality.
V. Conclusion

This paper has investigated the performance of dynamic PHEVs as a virtual UPQC. We have investigated the system current at different point of the network with PHEVs as virtual UPQC. The harmonics situation at load and source also investigated with virtual UPQC.

The obtained results from simulations show that PHEV have the capability to work as a virtual UPQC to improve power quality. It has been concluded that a lot of future research is needed to study the implementation of V2G technology in a power system. Several issues, such as battery ageing consequences, improvement of the control technique considering the smart grid technology could be the interesting topics in the future work.

References


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