PHEVs Park as Virtual Unified Power Flow Controllers

F. R. Islam, H. R. Pota*
School of Engineering and Information Technology (SEIT)
The University of New South Wales at Australian Defence Force Academy (UNSW@ADFA),
Canberra, ACT 2600, Australia
*corresponding author, e-mail: F.M.Islam@student.adfa.edu.au, H.R.Pota@adfa.edu.au*

Abstract

Unified power flow controllers (UPFCs) are FACTS devices which can fulfill multiple power-flow control objectives, such as the need for reactive shunt compensation, phase shifting and series compensation. However, as they are quite expensive, they are not widely used. In this paper, the potential of a plug-in hybrid electric vehicle (PHEV) in a vehicle-to-grid (V2G) mode of operation using a PHEV charging station to provide a low-cost solution to the design of a virtual UPFC is explained. A third-order dynamic battery model is used to represent the PHEV, and the simulations carried out demonstrate that a PHEV has the potential to work as a virtual UPFC to improve power quality.

Keywords: PHEVs, Virtual UPFC, Dynamic battery, PHEV's park, V2G Technology

1. Introduction

The increasing number of PHEV fleets penetrating the market provides an enormous opportunity to use V2G technology to improve the power quality of a utility grid. Statistical data show that more than 95% of personal vehicles remain parked during the day according to a regular schedule [1]. A PHEV owner expects his vehicle to be charged during working hours or the time it’s parked at home. Ideas for using a PHEV charging station during these periods as a spinning reserve [2], load leveler [3], external storage for renewable energy [4] and filter [5]-[6] have been introduced in various research studies. As reported in [7], a PHEV with a huge capacity battery is able to compensate reactive power to a utility grid while another study has demonstrated that a PHEV battery has the capability to serve as a static compensator (STATCOM) [8]. An effective and economical way of buying and selling electricity from a PHEV according to variable price curves has been reported in [9]-[10]. However, these and other previous studies have not investigated the dynamic behavior of a PHEV battery and its ability to deal with series and shunt compensating strategies as a UPFC does.

In this paper, a comprehensive way of utilizing PHEV batteries and their bidirectional chargers in a charging station as virtual UPFCs in a V2G mode of operation is demonstrated. A smart-park model with the dynamic behavior of a PHEV battery is developed and integrated in a real-life power system. Hybrid-electric power technologies and advances in battery make PHEVs a strong alternative to conventional vehicles and, by the year 2030, their penetration will be 25% [11]. They are the solution to the rising costs of petroleum coupled with increasing financial and energy security requirements and environmental concerns [12], [13]. A PHEV can be charged from both a household’s electrical connection and a charging station even when parked during the day. PHEVs give opportunity to design its bidirectional charger as UPFC converters. Any combination of the power system parameters (transmission voltage, line impedance and phase angle) which determine transmittable power can be controlled in real time using a UPFC which can be described as a generalized power flow controller capable of maintaining the certain amounts of real and reactive powers necessary under both normal and temporary system operating conditions. Compared with other FACTs devices, such as STATCOMs and thyristor-controlled series capacitors (TCSCs), it is evident that a UPFC is unique in its capability to control both real and reactive powers [14]. A basic UPFC structure is shown in Figure 1.

Although a UPFC is the most versatile FACTS controller developed so far, it is not widely used for power quality improvement due to its cost which, on average, is twice that of a STATCOM for each KVA [15] while, the most expensive components for the constitution of
FACTS or HVDC devices are their capacitors [16]. In this situation, this paper investigates the possibility of employing a PHEV as a UPFC through its bidirectional converter which has the capability to run in different operational modes according to need, as reported in [17].

The rest of this paper is organized as follows: Section II provides the virtual UPFC model; Section III the controller design; Section IV the test system design and simulation results; and Section VI brief concluding remarks and suggestions for future work.

![Basic single-line diagram of UPFC](image)

**Figure 1. Basic single-line diagram of UPFC**

### 2. Virtual UPFC Model

In order to design a virtual UPFC using a PHEV, it is essential to assess the PHEV’s interface with the power system and the dynamics of its battery. As a PHEV needs an electronic converter to connect it to an electrical network for battery charging, a bidirectional converter is considered here as the charger and a dynamic battery model for a PHEV which considers the dynamic responses of electrolytic temperature and the battery’s state-of-charge (SOC) is used [5], [6].

The range of PHEV driving required to evaluate battery capacity is considered to be 50 miles/day. As 0.3 kWh of battery energy is required to drive one mile, this means that the capacity of a PHEV battery will be 15 kWh [18], [19].

The controls of the bidirectional converters for the UPFC are designed for ± 20 MW of power transaction with the grid to represent a park with approximately 1334 vehicles which is a quite reasonable assumption for a typical city. To develop a suitable model of a PHEV, a dynamic model of a rechargeable battery [20], the elements of which are not constant as they depend on both the electrolytic temperature and SOC, is selected. The battery equivalent network is illustrated in Figure 3, where \( \theta \) represents the electrolytic temperature and \( I_m \) is an integral part of the total current \( I \), as shown in Figure 2.

![Battery equivalent network with parasitic branch](image)

**Figure 2. Battery equivalent network with parasitic branch**

![Battery equivalent network](image)

**Figure 3. Battery equivalent network**
Another part of the total current passes through the parasitic branch. The parasitic reaction is a continuous process that draws current but does not participate in the main reaction. The voltage at this branch is nearly equal to the voltage at the pin and the power dissipated into the real parts of impedances $Z_m$ and $Z_p$ is converted into heat. Impedance of the main reaction branch increases with an increasing charge and, as a result, the terminal voltage of the parasitic branch and the current ($I_p$) rise. At a battery’s full SOC, the impedance of the main reaction branch approaches infinity [20], [21].

This battery model can be represented as an RLC network, as shown in Figure 3, and the number of R-L-C blocks can be limited as the specific speeds of evolution of the electrical quantities evolve very rapidly for PHEVs [20].

The third-order dynamic battery model is designed considering the current, electrolytic temperature and SOC, and its dynamic equations are [20] -[22]:

\[
\dot{q}_c = \frac{i_d}{T_s} \\
\dot{i}_m = \frac{(i_d - i_m)}{T_m} \\
\dot{\theta} = -\frac{1}{C_\theta} \left[ P_i - \frac{\theta - Q_e}{R_\theta} \right] \\
V_{dc} = E_m - V_p(q_e, i_m) + V_e e^{-B_e q_e} - R_0 i_{dc}
\]

where $V_e$ represents the hysteresis phenomenon for the lead-acid battery during its charge and discharge cycles. The exponential voltage increases when the battery is charging regardless of its SOC. When the battery is discharging, the exponential voltage decreases immediately while $V_p$ depends on the sign of $i_m$ as:

\[
V_p(q_e, i_m) = \begin{cases} 
\frac{R_p i_m + K_p q_e}{SOC} & \text{if } i_m > 0 \text{(discharge)} \\
\frac{R_p i_m + K_p q_e}{q_e + 0.1} & \text{if } i_m < 0 \text{(charge)}
\end{cases}
\]

The equations for $E_m$, $R_0$, $R_1$ and $R_2$ are:

\[
E_m = E_{m0} - K_e(273 + \theta)(1 - SOC) \\
R_0 = R_{00}[1 + A_0(1 - SOC)] \\
R_1 = -R_{00}ln(DOC) \\
R_2 = \frac{R_{20} \exp[A_{21}(1 - SOC)]}{1 + \exp(A_{22} I_m/I)}
\]

where $E_{m0}$, $K_e$, $R_{00}$, $A_0$, $A_{21}$ and $A_{22}$ are constant for a particular battery.

The SOC and depth of charge (DOC) can be expressed as:

\[
SOC = \frac{Q_n - Q_e}{Q_n} = 1 - q_e
\]

\[
DOC = 1 - Q_n/C(\omega_{eq}, \Theta)
\]

where $C_\theta$, and $Ps$ are the battery’s thermal capacity and power, respectively, $R_0$ the thermal resistance, $Q_a$ the ambient temperature, $Q_e$ the extracted capacity in Ah, and $Q_n$ the rated
battery capacity in Ah. $K_c$, $E_m$, $E_{m0}$, $K_e$, $R_{01}$, $A_0$, $A_{21}$, and $A_{22}$ are constant for a particular battery the parameters are available in [20].

As the parasitic branch’s behavior is strongly nonlinear, its current can be expressed as:

$$I_p = V_p G_p \exp \left( \frac{V_p}{V_p} + A_p \left( 1 - \frac{\theta}{\theta_f} \right) \right)$$

The computation of $R_p$ gives the heat produced by the parasitic reaction by means of the Joule law:

$$P_s = R_p I_p^2$$

Therefore, our proposed UPFC model can be represented by Figure 4. Research has been carried out [8] to examine the P-Q capability of a PHEV battery and, as shown in Figure 5 that of a real battery [23] varies within ± 138 kW and ± 138 kVA respectively.

3. Controller Design

As the UPFC is realized as a combination of series and shunt converter-based FACTS devices with a common DC voltage ($V_{dc}$), we have two different strategies for controlling its converters using simple controller structures; the shunt converter by controlling
the AC and DC voltages to obtain the firing angle (α) and modulating amplitude (m) and the series converter by a simple decoupling controller for the active and reactive powers.

3.1 Shunt Converter Control

A bidirectional converter (a rectifier and an inverter) and a transformer with reactance \( x_{sh} \), as depicted in Figure 6, are used. The DC voltage is regulated by means of the converter’s \( m \) as [22]:

\[
m = \frac{x_{sh}}{V_s k V_{dc}} \sqrt{p_s^2 + \left( q_s + \frac{V_s^2}{x_{sh}} \right)^2}
\]

(12)

As the DC power of the battery (\( P_{dc} = V_{dc} I \)) is considered to be the real power in the network (\( p_s = P_{dc} \)), its link with the AC network is:

\[
p_s = \frac{V_s V}{x_{sh}} \sin(\theta_s - \theta_t) = V_{dc} I
\]

(13)

\[
q_s = \frac{V_s V}{x_{sh}} \cos(\theta_s - \theta_t) - \frac{V_s^2}{x_{sh}}
\]

(14)

where \( V_t = k m V_{dc} \) and the rectifier gain \( k = \sqrt{3/8} \). Therefore, the relationship between \( \theta_t \) and \( \theta_s \) can be expressed as:

\[
\theta_t = \theta_s + \sin\left(\frac{x_{sh} I}{k m V_s}\right)
\]

(15)

and the final equation for \( q_s \) is:

\[
q_s = \frac{V_s^2}{x_{sh}} - \frac{V_s k m V_{dc}}{x_{sh}} \sqrt{1 - \left(\frac{x_{sh} I}{k m V_s}\right)^2}
\]

(16)

where \( p_s \) is the real power, \( q_s \) the reactive power, \( V_s \) the voltage, \( \theta_s \) the phase angle at the connecting bus, and \( V_t \) and \( \theta_t \) the voltage and phase angle before the transformer, respectively. The PHEV is connected to the AC network through the bidirectional converter which is completed by the control that regulates \( m \) and \( \alpha \). Special care is taken to develop the operating limits of the converter, with both \( \alpha \) and \( m \) limited by the boundary conditions as:
\[
\alpha_{\text{min}} \leq \alpha \leq \alpha_{\text{max}} \\
m_{\text{min}} \leq m \leq m_{\text{max}}
\]

The PHEV's battery current \( i_m \) is subjected to a constant power control as:

\[
i_m = \frac{1}{T_m} \left( \frac{V_{dc}^{\text{lim}}}{E_{m0}} - i_m \right)
\]

The battery current set point is limited by the SOC and then the currents \( i_{\text{shd}} \) and \( i_{\text{shq}} \) are regulated through a set of PI controllers, as shown in Figure 7. \( V_{\text{shd}} \) and \( V_{\text{shq}} \) determine the \( m \) and \( \alpha \), respectively, passing through another set of PI controllers which can be expressed by the following equations:

\[
m = (K_m(V_{\text{ref}} - V_s) - m)/T
\]

\[
\dot{x}_a = K_i(V_{\text{ref}} - V_s)
\]

\[
0 = K_p(V_{\text{ref}} - V_s) + x_a - \alpha
\]

where \( V_s = \sqrt{V_{\text{shd}}^2 + V_{\text{shq}}^2} \)

![Figure 7. Modified decoupled P-Q controller for shunt converter [7]](image)

### 3.2 Series Converter Control

The decoupled P-Q controller shown in Figure 8 is used to control the series converter of the virtual UPFC. The output variables \( X_1 \) and \( X_2 \) of the PI controller are used to calculate the series converter's output voltages \( V_{\text{seq}} \) and \( V_{\text{seq}} \), respectively. The dynamic equations for the series converter can be expressed as [22]:

\[
\dot{x}_1 = K_i \left( \frac{2P_{\text{ref}}}{V_{kd}} - I_{kd} \right)
\]

\[
\dot{I}_{kd} = x_1 - KI_{kd} + K_p \left( \frac{2P_{\text{ref}}}{V_{kd}} - I_{kd} \right)
\]
\[ \dot{x}_2 = K_i \left( \frac{2Q_{k_{ref}}}{V_{kd}} - I_{kq} \right) \]
\[ \dot{I}_{kq} = x_2 - K_I x_{kq} + K_p \left( \frac{2Q_{k_{ref}}}{V_{kd}} - I_{kq} \right) \]

Other control parameters are:

\[ K = \frac{R_x + R_{se}}{X_x + X_{se}} \Omega \]
\[ V_{kd} = \sqrt{2} V_k \]
\[ V_{hd} = \sqrt{2} V_h \cos(\theta_k - \theta_h) \]
\[ V_{hq} = \sqrt{2} V_h \sin(\theta_k - \theta_h) \]

\[ x_1 = x_1^* + K_i \left( \frac{2P_{k_{ref}}}{V_{kd}} - \Omega I_{kd} \right) \]
\[ x_2 = x_2^* + K_i \left( \frac{2Q_{k_{ref}}}{V_{kd}} + \Omega I_{kd} \right) \]

\[ V_{sed} = V_{kd} - V_{kd} - \frac{X_x - X_{se}}{\Omega} X_2 \]
\[ V_{seq} = V_{kd} - \frac{X_x - X_{se}}{\Omega} X_2 \]

\[ V_{se} = \frac{1}{\sqrt{2}} \sqrt{V_{sed}^2 + V_{seq}^2} \]

\[ m_{se} = \sqrt{\frac{8}{3}} \left( \frac{V_{se}}{V_{dc}} \right) \]

where \( \Omega \) is the fundamental frequency base in rad/s.

![Diagram of Decoupled P-Q Controller](image)

**Figure 8. Decoupled P-Q controller for series converter [24]**

The DC voltage is controlled within its maximum and minimum limits by a set of PI controllers, as shown in Figure 9.
4 Test System Design
To validate the proposed UPFC model, the test system shown in Figure 10, which operates at 230 kV with two Thevinen impedance sources connected via transmission lines, and a T-tap terminated with a $\Delta$-Y transformer and rated at 230 kV/25 kV, is introduced. The Y-Y connected shunt transformer of the UPFC is rated at 20 MVA and 230kV/21kV, and the Y-$\Delta$ connected series transformer at 20 MVA and 92kV/21kV.

5 Simulation Results
In commendations to PHEV's Parks as virtual UPFC, two types of simulation results are presented. In the first phase of study, internal output and the reference value of currents are presented to know the characteristics of virtual UPFC. In the second phase of study, the achievement of the virtual UPFC is compared with a standard UPFC when it is connected amid bus 3 and bus 2 and a fault has been applied amid bus 4 and bus 5 at $t=0.5$ sec and abolish at $t=0.75$ Sec. Figure 11 and Figure 12 show the q axis current for shunt and series converter respectively and Figure 13 and Figure 14 are the current of q axis for shunt and series converter respectively. All the current show that the output d and q axis current of shunt and series converter follow the reference current before and after fault.

A comparison study has been made between a standard and the virtual UPFC to verify the performance of the proposed UPFC in the network shown in Figure 10. In Figure 15, red color shows the standard and green color shows the VUPFC's voltage output during the fault and normal condition where the performance of VUPFC is quite satisfactory with comparison of a standard UPFC.

![Figure 11. Shunt converter d axis current of Virtual UPFC](image1)

![Figure 12. Series converter d axis current of Virtual UPFC](image2)
Figure 13. Shunt converter q axis current of Virtual UPFC

Figure 14. Shunt converter q axis current of Virtual UPFC

Figure 15. Output voltage from UPFCs

Figure 16. Reactive power support from UPFCs

Figure 17. Real power support from UPFCs

Figure 18. Output DC voltage from VUPFC

The reactive and real power support shown in Figure 16 and Figure 17, from the VUPFC for the network are in the same level with comparison to standard UPFC but the oscillation in the output of VUPFC is much higher for both of the cases. In this work we have used very simple converter controllers, however by designing proper controllers this problem can be minimized. At Figure 18 the DC voltage from the PHEVs park is shown which assures the reference level.

6 Conclusion

The goal achieved via this study was an investigation into the performance of a dynamic PHEV as a virtual UPFC in terms of both the voltages of its series and shunt converters and the system’s current. To assess the accuracy of the designed system, we compared the output of
the virtual UPFC with a UPFC rated at the same standard. The results obtained from simulations showed that the PHEV had the capability to work as a virtual UPFC to improve power quality. However, a great deal of research is needed to study the implementation of V2G technology in a power system. Several issues, such as the consequences of battery ageing and achieving improvements in the control technique considering smart-grid technology to obtain better performances from the virtual UPFC could be interesting topics for future work.

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References