

Vehicle to grid system to design a centre node virtual unified power flow controller

F.R. Islam[✉] and M. Cirrincione

Centre node unified power flow controller can fulfil various power flow control objectives, such as the needs of reactive shunt and series compensation, phase shifting and ensure higher degree of control freedom. However, as they are expensive, they are not widely used. The potential of a low-cost solution that utilises the capabilities of plug in electric vehicle (PEV) in vehicle-to-grid mode of operation for the design of a centre node virtual unified power flow controller (CVUPFC) using PEV charging stations is explained. Simulations are performed to establish that the proposed CVUPFC improves the power quality utilising PEV charging stations as DC bus for the converters with higher degree of freedom to control.

Introduction: A unified power flow controller (UPFC) is one of the most multipurpose flexible alternating current transmission systems (FACTS) devices developed to date. Centre UPFC (CUPFC) is a modified UPFC with two series inverters and a shunt inverter in centre node, which offers more degree of freedom in control line (i.e. phase shifting, real power flow, reactive powers at both ends and voltage of the transmission line at the centre point) with better quality performance [1]. The expensive CUPFC is not widely utilised to maintain power quality, as the average cost of CUPFC is three times as much as for a static synchronous compensator (STATCOM) per kVA [2], and the prime cost for the construction of this FACTS device is the cost of capacitors and inverters.

The advances in battery technologies, improved safety and economic features make PEVs a smart choice against the traditional automobiles and this ensures their penetration in transportation system of almost 25% by the year 2020 in USA [3]. Charging PEV is possible from household electric supply or from a car park, even from a charging station. PEVs charging stations offer the possibility to design and control bidirectional chargers as CVUPFC converters.

Various researches have introduced the concept of utilising PEV as sources for reserve energy, for equal load distribution, peripheral storage for intermediate energy (i.e. solar and wind), virtual dynamic voltage restorer, employing as filter and STATCOM. The financial methods of electricity trading from PEV, also included in a number of articles [4]. However, these prior researches have not described the performances of PEV battery in connection with shunt, centre node and series compensating attributes as CVUPFC does.

Given these situations, this research results a smart method of using PEV's bidirectional charger and dynamic batteries as CVUPFC in V2G mode in a power network, considering that the vehicle will be charged from a charging station.

PEV battery modelling: In this Letter, PEVs are considered as dynamic batteries, connected with the grid using bidirectional converters [5]. The PEVs are considered with ± 12 kW active and ± 12 kVA reactive power capacity and with a rated current 30 A for the converters. The other parameters are used considering PEV, Escape 2010 designed by Ford, as shown in Table 1.

Table 1: Vehicle specification and drive system

Vehicle specification	Electrical drive	Charger system
Model – Escape 2010 Ford	Number of cells – 84	Charging voltage – 120 V
Output – 155 hp at 600 rpm	Cell voltage – 3.6	Charging current – 30 A
Curb weight – 1568 kg	System voltage – 302 V	Pack energy – 12 kWh

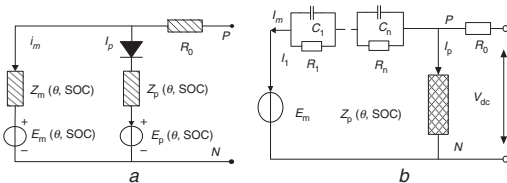


Fig. 1 Battery network

a Battery equivalent circuit including parasitic
b RC circuit

A third-order rechargeable dynamic battery model considering state of charge (SOC) and electrolyte temperature θ has been used [6] in this research. The equivalent circuit of the battery with parasitic branch is shown in Fig. 1a.

An RC network can be used to represent this battery with a limited number of blocks, since the dominant real poles of the system are limited in PEV [7], as shown in Fig. 1b.

The equations for this dynamic battery [6, 7] are

$$\dot{q} = i_{dc}/3600 \quad (1)$$

$$\dot{i}_m = (i_{dc} - i_m)/T_m \quad (2)$$

$$\dot{\theta} = -\frac{1}{C_\theta} \left[P_s - \frac{\theta - Q_a}{R_\theta} \right] \quad (3)$$

$$V_{dc} = E_m - V_p(q, i_m) + V_e e^{-B_e q} - R_0 i_{dc} \quad (4)$$

In this model, hysteresis phenomenon for battery charging and discharging is denoted by V_e and V_{dc} is directly proportional to the charging state, while the direction of the current, i_m cope the polarisation voltage V_p as

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

The SOC can be found using the following equation:

$$\text{SOC} = \frac{Q_n - Q_e}{Q_n} = 1 - q \quad (5)$$

CVUPFC design and control: The virtual CVUPFC for transmission line is shown in Fig. 2. A couple of modified decoupled PQ controllers which have outstanding performances and simple to employ in real time are used for both shunt and series converters.

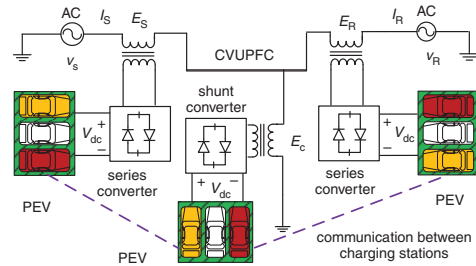


Fig. 2 Implementation of CVUPFC in transmission line

A transmission line with transmitting (sending) and receiving end voltages, V_S , and V_R , has been considered with the reactance of $j(X_S + X_R)$. A phase shifting is required as V_S and V_R have a large angle between them as shown in Fig. 3. Assuming CVUPFC and line losses are negligible, $\text{Re}(S_{SE}) = \text{Re}(-S_{RE})$, where S_{SE} and S_{RE} are the complex powers in the line and I_S and I_R are the corresponding sending end and the receiving end currents.

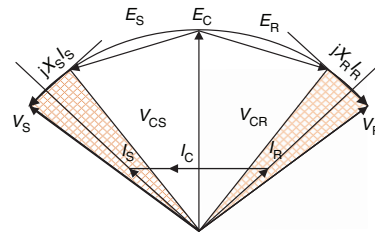


Fig. 3 Vector diagram of CVUPFC

The liberty to identify the reactive powers in S_{SE} and S_{RE} allows an intermediate path to exist for the centre node current, $I_C = I_S - I_R$.

The current phasor triangle of I_C , I_S , I_R in Fig. 3 gives an image of fundamental expenses for shifting phase, as shunt converter will provide the current I_C , considering the compensating path is at around the centre of the network, by maintaining X_S is roughly equal to X_R .

At the shunt connection, bidirectional converter of PEV is connected with the network and controlled the firing angle, α and modulating amplitude m .

The PEV battery current, i_m is given by (2), that for the shunt PEV is

$$\dot{i}_m = \frac{1}{T_m} \left[\frac{V_{dc}^{lim}}{E_{m0}} - i_m \right] \quad (6)$$

SOC is responsible to set the operating point of battery current and two different PI controllers regulate the currents i_{shq} and i_{shd} as shown in Fig. 4 [8]. E_{shdr} and E_{shqr} determine therefore the amplitude and firing angle, which can be expressed by

$$\dot{m} = (K_m(E_{ref} - E_c) - m)/T \quad (7)$$

$$\dot{x}_a = K_i(E_{ref} - E_c) \quad (8)$$

$$0 = K_p(E_{ref} - E_c) + x_a - \alpha \quad (9)$$

where $E_c = \sqrt{E_{shd}^2 + E_{shq}^2}$

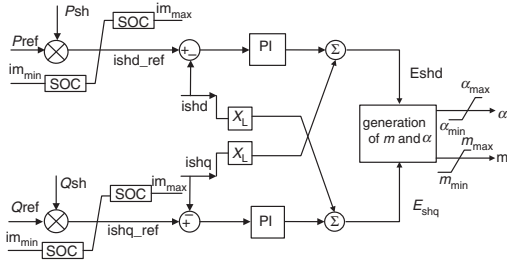


Fig. 4 Shunt converter control

To control the series converters of the CVUPFC, generalised output variables X_1 and X_2 are used to determine the voltages, V_{sed} and V_{seq} . The proportional and integral gains for both series and shunt converter controllers are given in Table 2.

Table 2: Proportional and integral gain

Series converter S	Series converter R	Shunt converter
$K_{p1} = 0.004$	$K_{p1} = 0.004$	$K_{p1} = 0.004$
$K_{i1} = 5.0$	$K_{i1} = 5.0$	$K_{i1} = 5.0$
$K_{p2} = 0.0017$	$K_{p2} = 0.0017$	$K_{p2} = 0.0017$
$K_{i2} = 0.4363$	$K_{p2} = 0.0017$	$K_{p2} = 0.0017$

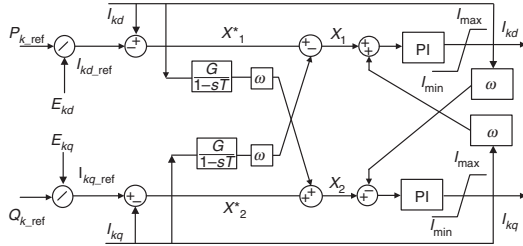


Fig. 5 Decoupled PQ controller for series converter

Series converter's dynamic equations are [6]

$$\dot{x}_1 = K_1 \left(\frac{2Pk_{ref}}{V_{kd}} - I_{kd} \right) \quad (10)$$

$$\dot{I}_{kd} = x_1 - KI_{kd} + K_p \left(\frac{2Pk_{ref}}{V_{kd}} - I_{kd} \right) \quad (11)$$

$$\dot{x}_2 = K_1 \left(\frac{2Qk_{ref}}{V_{kd}} - I_{kq} \right) \quad (12)$$

$$\dot{I}_{kq} = x_2 - KI_{kq} + K_p \left(\frac{2Qk_{ref}}{V_{kd}} - I_{kq} \right) \quad (13)$$

where ω is the fundamental frequency base in rad/s with all other variables in per unit. i_{min} is the minimum current, pk_{ref} is the active reference power and qk_{ref} is the reactive reference power, as shown in Fig. 5 [6].

Simulation results: The system of Fig. 2 has been simulated considering the total line reactance, $X_S + X_R = 0.275$ p.u. assuming that 1.0 p.u. power is transmitted across the line with the voltage angle $\delta = 17.4^\circ$. In the phase-shifting problem, it is assumed that the voltage angle between V_S and V_R is $\delta = 60^\circ$. Fig. 6 shows the response of the transmitted real power, P , to a 'step' command. Reactive powers Q_S and Q_R are set at zero to identify the response properly and the aim is fulfilled by ensuring the currents and voltages are in phase. The freedom of control is utilised to keep the centre-node voltage, V_C , real power P and reactive powers at both ends (Q_S, Q_R) constant before and after the transient.

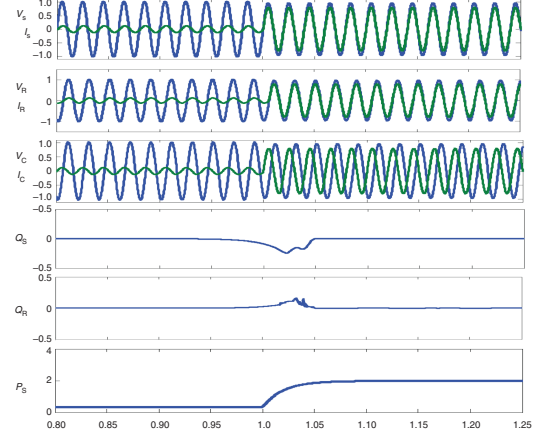


Fig. 6 Voltage, current, real and reactive powers response to step command

Conclusion: This Letter proposes and models a CVUPFC based on decoupled PQ control using V2G technology with PEV. The ability of the CVUPFC to maintain power quality under a step change in power has been justified through time domain simulations. As this research is a fundamental step to design this virtual FACTS device, simple but reliable controllers are used, hence a variety of intelligent controllers can be used to improve and compare the performances of CVUPFC. Implementation of these devices in smart grid or microgrid environment could be an interesting research topic in future.

Acknowledgment: This work was supported by the School of Engineering and Physics, the University of the South Pacific, Fiji.

© The Institution of Engineering and Technology 2016

Submitted: 5 March 2016

doi: 10.1049/el.2016.0534

One or more of the Figures in this Letter are available in colour online.

F.R. Islam and M. Cirrincione (SEP, FSTE, USP, Suva, Fiji)

✉ E-mail: fmrahiul.islam@usp.ac.fj

References

- Hosseini, S.H., and Ajami, A.: 'Modeling and controlling of a new FACTS device (C-UPFC) for transmission line applications'. In Proc. Int. Conf. on Electrical Machines and Systems, Nanjing, China, Sept 2005, pp. 1267–1272
- Mathur, R., and Varma, R.: 'Thyristor-based FACTS controllers for electrical transmission systems', New York: John Wiley & Sons, 2002, Ch. 17–18
- Hadley, S.W., and Tsvetkova, A.A.: 'Potential impact of plug-in-hybrid electric vehicles on regional power generation', *Electr. J.*, 2009, **22**, (10), pp. 56–68
- Islam, F.R., and Pota, H.R.: 'Integrating smart PHEVs in future smart grid'. In Mahmud, A. (Ed.): 'Renewable energy integration' Singapore: Springer, 2014, Ch. 11
- Kisacikoglu, M.C., Ozpineci, B., and Tolbert, L.M.: 'Examination of a PHEV bidirectional charger system for V2G reactive power compensation'. In Proc. Applied Power Electronics Conf. and Exposition (APEC), Palm Springs, CA, Feb 2010, pp. 458–465
- Milano, F.: 'Power system modelling and scripting' (Springer-Verlag, New York, 2010), Ch. 17-18
- Ceraolo, M.: 'New dynamical models of lead-acid batteries', *IEEE Trans. Power Syst.*, 2000, **15**, (4), pp. 184–1190
- Islam, F.R., and Pota, H.R.: 'V2G technology to improve wind power quality and stability'. In Proc. Australian Control Conf. (AUCC), Melbourne, VIC, September 2011, pp. 452–457