

# Nonlinear Controller Design for Vehicle-to-Grid (V2G) Systems to Enhance Power Quality and Power System Stability

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**Abstract:** A nonlinear controller design technique, for the enhancement of power quality and power system stability in a vehicle-to-grid (V2G) system, is proposed in this paper. The dynamical model of a V2G system is first developed and then the controller is designed based on the partial feedback linearization of the developed model. The control scheme is developed in such a way that converters in V2G systems are capable of injecting both active and reactive power into the grid. The implementation of the proposed controller requires the stabilization of internal dynamics of V2G systems as it transforms the system into a partly linear and an autonomous system with internal dynamics. The stability of internal dynamics of V2G systems is also discussed in this paper. Finally, the performance of the proposed control scheme is evaluated on a simple test system in terms of power quality and system stability enhancement. From the simulation result it is found that the designed nonlinear controller provides excellence performance in improving power quality and stability of whole system.

*Keywords:* Power quality, power system stability, vehicle-to-grid (V2G) systems, partial feedback linearization, internal dynamics.

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## 1. INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs), which can be recharged from and discharged to the power grid by plugging into electrical outlets, are becoming increasingly popular in order to address energy and environmental issues as these vehicles reduce carbon emissions and provide ancillary services to the power grid. PHEVs can either be used as loads in charging phase of batteries from the grid or as generators in discharging phase when they are not in use for driving which is also known as vehicle-to-grid (V2G) operation. These features of PHEVs pose several opportunities and challenges in energy management strategies of modern power systems (Galus et al., 2010).

The integration of huge number of PHEVs into the grid as loads might cause several problems such as transformer or line overloading and voltage stability (Papadopoulos et al., 2012; Hilshey et al., 2013). By considering these problems, several investigations have been performed in (Das et al., 2013; Yang et al., 2013) so that PHEVs could be advantageous for power system operations. For example, effective charging and discharging schedules of PHEVs

could support the integration of renewable energy sources by storing energy during the off-peak and deliver it back to the grid during the peak. Numerous research activities have been performed effective charging and discharging schemes and some most recent could be found in (He et al., 2013; Gunter et al., 2013).

In a V2G system, batteries of PHEVs act as distributed energy resources by locally meeting the demand during peak hours and thus, a V2G system reduces the stress on overloaded distribution systems. The amount of power delivered from vehicles to the grid is estimated by the aggregator in which a communication link is used to communicate between vehicle owners and distribution network service providers (DNSPs) (Han et al., 2010). A sudden discharge of batteries used in V2G systems may cause a voltage variation problem in distribution networks at which they are connected and this in turns causes voltage stability problems. Moreover, power electronic inverters are used as interfacing units between the grid and batteries of PHEVs for which an effective switching scheme is essential to maintain the power quality and stability of whole system. Therefore, the design of a high performance

controller is a prominent issue which has the capability to mitigate the voltage variation problem through reactive power management and enhances the power quality of distribution networks.

Although a great deal of attention has been paid for the investigation of impacts of PHEVs on distribution networks and optimal scheduling of charging and discharging of PHEVs, a very little work has been done on the controller design for V2G operations of PHEVs. A fuzzy-based frequency controller is proposed in (Datta and Senjyu, 2012) to alleviate frequency fluctuations and to reduce power fluctuations in tie-lines with an application to V2G systems. The approach presented in (Datta and Senjyu, 2012) provides satisfactory results for controlling active power but the reactive power control is uncovered which is a key factor for maintaining voltage stability. The control of power flow has been demonstrated using a fuzzy logic controller in (Singhand et al., 2012) for voltage compensations and peak shavings. However the main limitations of fuzzy logic controllers are that a fuzzy system cannot fully capture the dynamical model of V2G systems and require more fine tuning and simulation before making it operational (Khayyam et al., 2012). Therefore, it is essential to consider model-based control approach to enhance the power quality and stability of V2G systems.

The design of linear and nonlinear controllers based on the detailed mathematical model of V2G systems could be worthy in order to maintain the stable operation of such systems with high power quality. Feedback linearization method is a widely used model-based nonlinear controller design technique which transforms a nonlinear system into a fully linear or a partly linear equivalent system by canceling the inherent nonlinearities within the system. Linear control design techniques can be employed to design a suitable controller for the linearized system (Isidori, 2nd Edition, 1989; Slotine and Li, 1991). When feedback linearization transforms a nonlinear system into fully linear system, the approach is called *exact feedback linearization* and if the system is transformed into a partially linearized system, the approach is known as *partial feedback linearization* (Isidori, 2nd Edition, 1989). Since feedback linearization cancels nonlinearities by introducing nonlinear term in the control law, the feedback linearized system is independent of operating points. The feedback linearization technique allows effective switching schemes for the interfacing inverters with distributed energy resources (Mahmud et al., 2012b,c)

The aim of this paper is to design a partial feedback linearizing controller for a V2G system and the control objectives are set as both active and reactive power. Since the partial feedback linearization is a model-based approach, a comprehensive mathematical model of V2G systems is formulated in this paper. The applicability and implementability of the proposed control scheme is tested through the feedback linearizability and stability of internal dynamics of V2G systems. The superiority of the proposed control scheme is investigated through simulation results under different operating scenarios and compared to that of a proportional-integral (PI) controller..

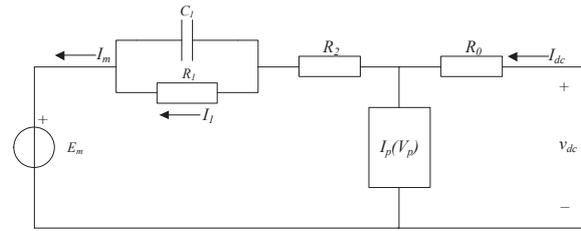


Fig. 1. Equivalent circuit diagram of a battery

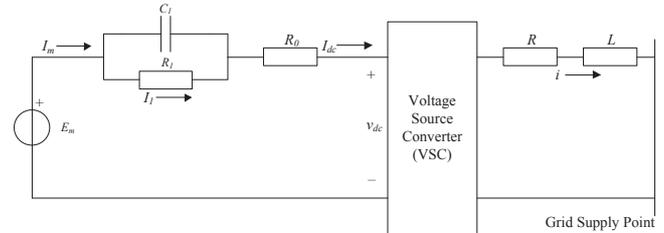


Fig. 2. Schematic diagram of a V2G System

## 2. MATHEMATICAL MODELING OF V2G SYSTEM

In this section, the mathematical model of a V2G system is developed. However before designing the main V2G system, a battery model is briefly reviewed as this is a major part of a V2G system. The most commonly used battery model is proposed in (Ceraolo, 2000) and the electrical circuit model of this battery is shown in Fig.1. In the model as described in (Ceraolo, 2000) and presented by Fig.1, the charge stored in the battery is the integral of only a part  $I_m$  of the total current  $I_{dc}$  entering the battery. The detailed of battery elements such as resistors ( $R_0$ ,  $R_1$ , and  $R_2$ ), capacitor ( $C_1$ ), and internal voltage ( $E_m$ ) can be seen in (Ceraolo, 2000). Since parasitic reactions often present in the battery, nonreversible parasitic branch models (with subscript  $p$  in Fig. 1) draw some current but does not participate in the main, reversible, reaction. It is noted that during discharge  $R_2 \cong 0$  and  $I_p \cong 0$  and when discharge behavior is to be simulated, the whole parasitic branch can be omitted (Ceraolo, 2000). Thus, a V2G system with the revised battery model is shown in Fig. 2.

From Fig. 2, it can be seen that in a V2G system  $I_m = I_{dc}$ . Now by applying Kirchhoff's current law (KCL) at the node where the resistor  $R_1$  and capacitor  $C_1$  are connected in parallel, we can write

$$I_{dc} = I_1 + C_1 \frac{dV_{C_1}}{dt} \quad (1)$$

where  $V_{C_1}$  is the voltage across  $C_1$  which is also the voltage across  $R_1$  and thus,  $V_{C_1} = I_1 R_1$ . Using this relationship, equation (1) can be simplified as

$$\frac{dI_1}{dt} = \frac{1}{\tau_1} (I_{dc} - I_1) \quad (2)$$

where  $\tau_1 = R_1 C_1$ . Now by applying Kirchhoff's voltage law (KVL) at the output-side of the inverter, i.e., at the grid-side, we can write

$$\frac{di}{dt} = -\frac{R}{L} i + m \frac{v_{dc}}{L} - e \quad (3)$$

where  $m$  represents the switching action of the converter which is a function of modulation index and firing angle,  $R$  is the resistance of the connecting line,  $i$  is the output current of the inverter,  $L$  is the combination of filter and connecting line inductance.

Equations (2) and (3) represent the time-variant model of a V2G system. But for the purpose of analysis and control, it is essential to transform the model into time-invariant system. To do this, the V2G system can be transformed into  $dq$ -frame which can be written as (Mahmud et al., 2012a)

$$\begin{aligned} \dot{I}_1 &= \frac{1}{\tau_1} (M_d I_d + M_q I_q - I_1) \\ \dot{I}_d &= -\frac{R}{L} I_d + \omega I_q - \frac{E_d}{L} + \frac{v_{dc}}{L} M_d \\ \dot{I}_q &= -\omega I_d - \frac{R}{L} I_q - \frac{E_q}{L} + \frac{v_{dc}}{L} M_q \end{aligned} \quad (4)$$

with

$$I_{dc} = mi = M_d I_d + M_q I_q$$

where  $\omega$  is the angular frequency;  $M_d$  and  $M_q$  are the switching functions in  $d$  and  $q$  frame respectively;  $I_d$  and  $I_q$  are the currents in  $d$  and  $q$ -frame respectively; and  $E_d$  and  $E_q$  are the grid voltages in  $d$  and  $q$ -frame respectively. In  $dq$ -frame, the active power ( $P$ ) and reactive power ( $Q$ ) delivered from the vehicle into the grid can be written as

$$\begin{aligned} P &= E_q I_q + E_d I_d \\ Q &= E_q I_d - E_d I_q \end{aligned} \quad (5)$$

In  $dq$  rotating frame, it can be assumed that  $E_d = 0$  (Kim, 2006; Mahmud et al., 2012c) and in this case, equation (5) can be simplified as

$$\begin{aligned} P &= E_q I_q \\ Q &= E_q I_d \end{aligned} \quad (6)$$

Equation (4) represents the completed dynamical model of a V2G system. The control objective is to design a nonlinear switching scheme for the V2G system as represented by equation (4) in order to deliver high quality active and reactive power into the grid. From equation (6), it can be seen that that quality of the active and reactive power depends on currents,  $I_d$  and  $I_q$  as there is nothing to do with the grid voltage components ( $E_d$  &  $E_q$ ) in  $dq$ -frame. Therefore, the control objective can be achieved by regulating the currents,  $I_d$  and  $I_q$  which can be selected as output functions of the V2G system.

### 3. FEEDBACK LINEARIZATION AND FEEDBACK LINEARIZABILITY OF V2G SYSTEM

The mathematical model of a V2G system as represented by equation (4) can be written in the following form of a nonlinear multi-input multi-output (MIMO) system equation:

$$\begin{aligned} \dot{x} &= f(x) + g_1(x)u_1 + g_2(x)u_2 \\ y_1 &= h_1(x) \\ y_2 &= h_2(x) \end{aligned} \quad (7)$$

where

$$x = \begin{bmatrix} I_1 \\ I_d \\ I_q \end{bmatrix}, \quad f(x) = \begin{bmatrix} -\frac{1}{\tau_1} I_1 \\ -\frac{R}{L} I_d + \omega I_q - \frac{E_d}{L} \\ -\omega I_d - \frac{R}{L} I_q - \frac{E_q}{L} \end{bmatrix},$$

$$g(x) = \begin{bmatrix} \frac{I_d}{L} & \frac{I_q}{L} \\ \frac{v_{dc}}{L} & \frac{v_{dc}}{L} \\ 0 & 0 \end{bmatrix}, \quad u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} M_d \\ M_q \end{bmatrix}, \quad \text{and } y = \begin{bmatrix} I_d \\ I_q \end{bmatrix}$$

Based on this nominal mathematical model, an overview of feedback linearizing controller design and feedback linearizability of V2G systems are discussed in the following two subsections.

#### 3.1 Overview of Feedback Linearization

The design of feedback linearizing controller depends on the feedback linearizability of the system and this feedback linearizability is defined by the relative degree of the system (Isidori, 2nd Edition, 1989). The relative degree of the system in turns depends on output functions of the V2G system. The mathematical model of a V2G system as shown by equation (4) can be linearized using feedback linearization when some conditions as described latter are satisfied. Consider the following nonlinear coordinate transformation ( $z = \phi(x)$ ) for the aforementioned V2G system.

$$z = \left[ h_1 \quad L_f h_1 \quad \dots \quad L_f^{r_1-1} h_1 \quad h_2 \quad L_f h_2 \quad \dots \quad L_f^{r_2-1} h_2 \right]^T \quad (8)$$

where  $r_1 < n$  and  $r_2 < n$  are the relative degree corresponding to output functions  $h_1(x)$  and  $h_2(x)$ , respectively,  $L_f h_i(x) = \frac{\partial h_i}{\partial x} f(x)$  is the Lie derivative of  $h_i(x)$ ,  $i = 1, 2$  along  $f(x)$  (Isidori, 2nd Edition, 1989). The change of coordinate (8) transforms the nonlinear system (7) from  $x$  to  $z$  coordinates provided that the following conditions are satisfied for:

$$\begin{aligned} L_g L_f^k h_i(x) &= 0; \quad k < r_i - 1 \\ L_g L_f^{r_i-1} h_i(x) &\neq 0 \\ n &= \sum_{i=1}^N r_i \end{aligned} \quad (9)$$

where  $L_g L_f h_i(x)$  is the Lie derivative of  $L_f h_i(x)$  along  $g(x)$ . The linearized system can be expressed as follows:

$$\dot{z} = Az + Bv \quad (10)$$

where  $A$  is the system matrix,  $B$  is the input matrix, and  $v$  is the new linear control input for the feedback linearized system.

When  $(r_1 + r_2) < n$ , only partial feedback linearization is possible, i.e., some states are transformed through nonlinear coordinate transformation and some are not. The new states of a partially feedback linearized system can be written as

$$z = \phi(x) = [\tilde{z} \quad \hat{z}]^T \quad (11)$$

where  $\tilde{z}$  represents the state vector obtained from nonlinear coordinate transformation of order  $r_1 + r_2$  and  $\hat{z}$  the

state vector of the nonlinear (remaining) part of order  $n - (r_1 + r_2)$ . The dynamic of  $\hat{z}$  is called the internal dynamic of the system which needs to be stable in order to design and implement a partial feedback linearizing controller for the following partially linearized system.

$$\dot{\hat{z}} = \tilde{A}\tilde{z} + \tilde{B}\tilde{v} \quad (12)$$

where  $\tilde{A}$  is the system matrix,  $\tilde{B}$  is the input matrix, and  $\tilde{v}$  is the new linear control input for the partially linearized system. The developed V2G system model could be exactly or partially linearized and the feedback linearizability of a V2G system is shown in the following subsection.

### 3.2 Feedback Linearizability of V2G Systems

The feedback linearizability of the V2G system represented by equation (7) can be obtained by calculating the total relative degree ( $r$ ) of the system. The relative degree corresponding to the first output function  $h_1(x) = I_d$  can be calculated as

$$L_g L_f^{1-1} h_1(x) = L_g h_1(x) = \frac{v_{dc}}{L} \neq 0 \quad (13)$$

where  $r_1 = 1$ . Similarly, the relative degree corresponding to the other output function  $h_2(x) = I_q$  can be calculated as follows

$$L_g L_f^{1-1} h_2(x) = L_g h_2(x) = \frac{v_{dc}}{L} \neq 0 \quad (14)$$

which indicates that  $r_2 = 1$ . Therefore, the total relative degree  $r = r_1 + r_2 = 2$  and this means that  $(r_1 + r_2) < n$  as  $n = 3$ . From this, it can be said that the V2G system is partially linearized and partial feedback linearization approach needs to be used to design the controller for this system. The design of a partial feedback linearizing controller for V2G system is shown in the following section.

## 4. PARTIAL FEEDBACK LINEARIZING CONTROLLER DESIGN FOR V2G SYSTEMS

The essential steps to design the partial feedback linearizing controller for V2G systems can be discussed as follows:

- **Step 1:** Nonlinear coordinate transformation and partial linearization of V2G systems

A nonlinear coordinate transformation can be written as

$$\tilde{z} = \tilde{\phi}(x) \quad (15)$$

where  $\tilde{\phi}$  is the function of  $x$ . For a V2G system, we choose

$$\tilde{z}_1 = \tilde{\phi}_1(x) = h_1(x) = I_d \quad (16)$$

and

$$\tilde{z}_2 = \tilde{\phi}_2(x) = h_2(x) = v \quad (17)$$

Using the above transformation, the partially linearized system can be obtained as follows:

$$\dot{\tilde{z}}_1 = \frac{\partial h_1(x)}{\partial x} \dot{x} = L_f h_1(x) + L_{g_1} h_1(x) u_1 + L_{g_2} h_1(x) u_2$$

$$\dot{\tilde{z}}_2 = \frac{\partial h_2(x)}{\partial x} \dot{x} = L_f h_2(x) + L_{g_1} h_2(x) u_1 + L_{g_2} h_2(x) u_2$$

For the V2G system,

$$\begin{aligned} \dot{\tilde{z}}_1 &= -\frac{R}{L} I_d + \omega I_q - \frac{E_d}{L} + \frac{v_{dc}}{L} M_d \\ \dot{\tilde{z}}_2 &= -\omega I_d - \frac{R}{L} I_q - \frac{E_q}{L} + \frac{v_{dc}}{L} M_q \end{aligned} \quad (18)$$

The above system can be written in the following linearized form:

$$\begin{aligned} \dot{\tilde{z}}_1 &= \tilde{v}_1 \\ \dot{\tilde{z}}_2 &= \tilde{v}_2 \end{aligned} \quad (19)$$

where  $\tilde{v}_1$  and  $\tilde{v}_2$  are the linear control inputs which can be designed using any linear control technique and can be expressed as

$$\begin{aligned} \tilde{v}_1 &= -\frac{R}{L} I_d + \omega I_q - \frac{E_d}{L} + \frac{v_{dc}}{L} M_d \\ \tilde{v}_2 &= -\omega I_d - \frac{R}{L} I_q - \frac{E_q}{L} + \frac{v_{dc}}{L} M_q \end{aligned} \quad (20)$$

However before designing and implementing controller through partial feedback linearization, it is essential to check the stability of internal dynamics of the V2G system which is discussed in the next step.

- **Step 2:** Stability of internal dynamics of V2G Systems

In the previous step, the third-order V2G system is transformed into a second-order system representing the linear dynamics of the system. Desired performance of the external dynamics can be obtained through design and implementation of a linear controller. However, to ensure stability, the control law needs to be chosen in such a way that

$$\lim_{t \rightarrow \infty} h_i(x) \rightarrow 0$$

which implies that the state of a linear system decays to zero as time approached to infinity, i.e.,  $[\tilde{z}_1 \ \tilde{z}_2 \ \dots \ \tilde{z}_r]^T \rightarrow 0$ ;  $t \rightarrow \infty$ . For the V2G system considered in this work, this means that at steady-state

$$\begin{aligned} \tilde{z}_1 &= 0 \\ \tilde{z}_2 &= 0 \end{aligned} \quad (21)$$

Let the remaining nonlinear state be expressed by the following nonlinear function  $\hat{z} = \hat{\phi}(x)$ . To ensure stability, this needs to be selected in such a way that it must satisfy the following conditions (Lu et al., 2001):

$$\begin{aligned} L_{g_1} \hat{\phi}(x) &= 0 \\ L_{g_2} \hat{\phi}(x) &= 0 \end{aligned} \quad (22)$$

For the developed V2G system model, equation (22) will be satisfied if we chose

$$\hat{\phi}(x) = \hat{z} = -\tau_1 I_1 + \frac{1}{2} \frac{L}{v_{dc}} I_d^2 + \frac{1}{2} \frac{L}{v_{dc}} I_q^2 \quad (23)$$

Thus, the remaining dynamics of the V2G system can be expressed as follows:

$$\dot{\hat{z}} = L_f \hat{\phi}(x) = -\tau_1 f_1 + \frac{L}{v_{dc}} I_d f_2 + \frac{L}{v_{dc}} I_q f_3 \quad (24)$$

Since  $I_d = h_1 = \tilde{z}_1$  and  $I_q = h_2 = \tilde{z}_2$ , equation (24) can be written as

$$\dot{\hat{z}} = L_f \hat{\phi}(x) = -\tau_1 f_1 + \frac{L}{v_{dc}} \tilde{z}_1 f_2 + \frac{L}{v_{dc}} \tilde{z}_2 f_3 \quad (25)$$

Using equation (21), equation (25) can be simplified as

$$\dot{\hat{z}} = I_1 \quad (26)$$

From equation (23),  $I_1$  can be calculated as

$$I_1 = \frac{1}{\tau_1} \left[ \frac{1}{2} \frac{L}{v_{dc}} I_d^2 + \frac{1}{2} \frac{L}{v_{dc}} I_q^2 - \hat{z} \right] \quad (27)$$

and replacing  $I_d$  and  $I_q$  with  $\tilde{z}_1$  and  $\tilde{z}_2$ , respectively and using their values from equation (21), equation (27) can be written as

$$I_1 = -\frac{1}{\tau_1} \hat{z} \quad (28)$$

Therefore, substituting the value of  $I_1$  from equation (28) into equation (26), we obtain

$$\dot{\hat{z}} = -\frac{1}{\tau_1} \hat{z} \quad (29)$$

Equation (29) represents stable internal dynamics of the V2G system and therefore partial feedback linearizing controller can be designed for the V2G system. It is also clear that the proposed partial feedback linearizing scheme divides the dynamics of V2G systems into two parts: one is the external dynamics as described in the previous step, and the other is the internal dynamics which needs to be stable to design the controller. The derivation of the proposed control law is shown in the following step.

• **Step 3:** Derivation of control law

For the V2G system, the original control inputs in  $dq$ -frame are  $M_d$  and  $M_q$  and the linear control inputs are  $\tilde{v}_1$  and  $\tilde{v}_2$ . From equation (20), the original control laws  $M_d$  and  $M_q$  can be obtained as follows

$$\begin{aligned} M_d &= \frac{1}{v_{dc}} [L\tilde{v}_1 + RI_d - \omega LI_q + E_d] \\ M_q &= \frac{1}{v_{dc}} [L\tilde{v}_2 + \omega LI_d + RI_q + E_q] \end{aligned} \quad (30)$$

Equation (30) is the final control law for the V2G system to deliver active and reactive power into the grid. At this point, the only issue to complete the controller design is to determine the linear control inputs,  $\tilde{v}_1$  and  $\tilde{v}_2$ . In this paper, PI controllers are used and the structures of the two PI controllers are chosen as follows

$$\begin{aligned} \tilde{v}_1 &= k_{1p}(I_{dref} - I_d) + k_{1i} \int_0^t (I_{dref} - I_d) dt \\ \tilde{v}_2 &= k_{2p}(I_{qref} - I_q) + k_{2i} \int_0^t (I_{qref} - I_q) dt \end{aligned} \quad (31)$$

The gains need to be selected in such a way that the output follows the reference current to minimize the error. In this paper, the gains are set as follows:

$$k_{1p} = 2I_{dref}, \quad k_{1i} = I_{dref}^2$$

and

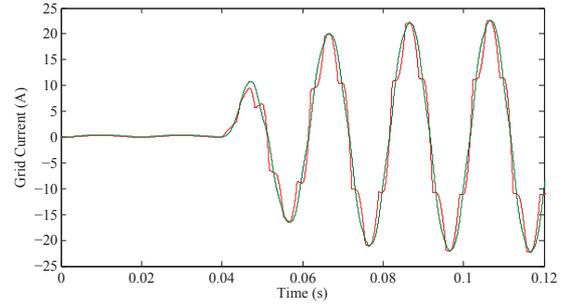


Fig. 3. Grid current at unity power factor (Green line–proposed controller and red line–PI controller)

$$k_{2p} = 2I_{qref}, \quad k_{2i} = I_{qref}^2$$

The reference values  $I_{dref}$  and  $I_{qref}$  can be calculated from equation (6) as

$$\begin{aligned} I_{qref} &= \frac{P_{ref}}{E_q} \\ I_{dref} &= \frac{Q_{ref}}{E_d} \end{aligned}$$

The performance of the designed controller is evaluated in the following section.

## 5. CONTROLLER PERFORMANCE EVALUATION

The performance of the designed controller is evaluated on a test V2G system as shown in Fig. 2 in which the vehicle is supplying a residential area, i.e., single-phase grid supply point. Since the main task of PHEVs are commutation, a minimum state of charge (SOC) needs to be maintained in order to deliver power into the grid. In this paper, the minimum SOC is considered as 30 per cent. The following equation is used to calculate the total available energy of PHEVs during discharging (Singhand et al., 2012)

$$S_{discharging} = P_b \times N \times SOC_{min}$$

where  $S_{discharging}$  is the total available energy for discharging to support the grid,  $P_b$  is the kWh of batteries,  $N$  is the number of vehicles connected to the grid, and  $SOC_{min}$  is the minimum SOC which is considered as 30 per cent. In this work, 15 PHEVs are connected to the grid and each of them with a battery rating of 4.4 kWh. Therefore the total available energy is 26.4 kWh. The other parameters of the battery and grid are provided in the Appendix A. The batteries of PHEVs are delivering power to the grid to supply a load of 5 KVA in a residential area and this information is provided by the aggregator.

When the power factor of the load is considered as unity, no reactive power will be delivered into the grid as the grid voltage and current will be in phase with each other. In this case, 5 kW power will be delivered into the grid and the corresponding current into the grid will be 22.72 A which is shown in Fig. 3. The output current of the inverter does not contain any harmonic with the designed controller as this is a pure sinusoidal signal which is shown by the green line in Fig. 3. But a conventional proportional integral (PI) controller which is designed for the unity

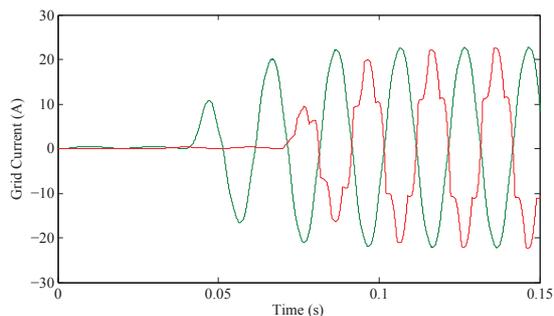


Fig. 4. Grid current at 0.8 power factor (Green line—proposed controller and red line—PI controller)

power factor operation of the V2G system, contains some harmonics (red line in Fig. 3).

Now if the V2G system needs to operate at a power factor other than unity, the grid voltage and current will not be in phase. In this case, some reactive power will be delivered into the grid. If the power factor is considered as 0.8, the active power which needs to be delivered into the grid will be 4 kW and that of reactive power will be 3 kVAr. In this case, the designed controller acts in a similar way as considered to the previous case (green line in Fig. 4). But the response of the conventional PI controller will be slower (red line in Fig. 4) as the reference active and reactive power have been changed.

## 6. CONCLUSIONS

A new dynamical model of a V2G system has been developed and a partial feedback linearizing controller has been designed for improving the power quality and stability. The justification, of using the proposed control approach, has also been provided for through the feedback linearizability of the developed V2G system model along with the inclusion of the stability of internal dynamics. Simulation results clearly indicate that the proposed approach improves the power quality significantly as compared to the conventional PI controller and enhance the stability of V2G systems as it is independent of operating conditions. The proposed controller acts faster than a PI controller during the changes in operating conditions which saves a huge amount of power. Future works will consider the design and implementation of such controller for a large-scale operation.

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## Appendix A. SYSTEM PARAMETERS

Battery Parameters:

$$R_1=0.4 \text{ m}\Omega, \tau_1=7200 \text{ s}, R_0=2 \text{ m}\Omega$$

Grid Parameters:

$$\text{Grid voltage (rms)}=220 \text{ V, Frequency}=50 \text{ Hz, } R=0.1 \Omega, L=10 \text{ mH}$$