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A Hybrid Multi-Loop Controlled FACTS-Based Smart V2G Battery Charger

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Abstract-The paper presents a flexible hybrid FACTS based AC-DC interface scheme with Flexible AC Transmission System Neutral Point Switched Filter Compensator (NPSFC) stabilization scheme developed by the Second Author to improve power quality and energy utilization in future Smart Grid-V2G Electric Vehicle (EV) Fast Battery Charging Stations. The FACTS-based filter compensation scheme proposed in this paper is equipped with a novel multi-loop dynamic error driven time de-scaled controller to enhance power factor, stabilize AC and DC side Common Bus voltages, ensure efficient energy utilization, and halt inrush current especially under fast battery charging modes. The FACTS-based hybrid filter compensator is a pulse width modulated/switched capacitor compensation scheme which uses IGBT/MOSFET switches. In addition, a revised controller is designed to improve the utilization of the DC bus voltage in combination with a Green Plug Filter Compensator (GPFC) device. GPFC device is controlled by a novel dual-loop controller which handles the voltage and current of the DC side of the rectifier. Output signals of the controllers are the inputs for a weighted-modified-PID which its output feeds the sinusoidal Pulse Width Modulation (PWM) block. In other words, the control signals of the controllers are used for regulating the PWM (on-off) pulsing sequences. The unified scheme is validated using MATLAB/SIMULINK toolbox.

Keywords-Electric Vehicles, Dynamic Error Driven Controller, FACTS (NPSFC), Battery Charging Scheme.

1. Introduction

The recent development in Electric Vehicle (EV) technology is driven by the need to reduce fossil fuel consumption, global energy demand, and climate changes due to carbon dioxide emissions, and decrease dependence to fossil fuels and combustion engine vehicles. Accordingly, the more effective and convenient solution is using the new generation of Green Electric Vehicles which are charged by electric energy obtained from renewable energy sources.

Electric Vehicles are supplied by batteries which can be recharged through connecting to external power sources [1]. Exceptional issue in this regard is that these sources can be renewable energy supplies such as solar, wind, and Photo Voltaic (PV) arrays which feed EVs in Vehicle to Grid (V2G) power stations and Vehicle to House (V2H) schemes [2-3]. Owing to accelerated use of EV, a great number of battery chargers are required to feed battery packs [4]. Due to limited charge capacity of battery packs, they need to be recharged frequently, so it is desirable to do charging as quickly as possible [5]. The capability to increase the rate of charging is currently behind new existing technology for efficient, durable, and fast charging battery classes. Dominant parameters that define the charging modes are the current capacity of the DC source, thermal limitations of the charger, and thermal and chemical limitations of the battery [6]. Due to these limitations, different battery types, charging schemes, and charger classes have been proposed [7]. A newly introduced battery charging with energy management control strategy that uses PV is based on a dynamic energy management algorithm to connect directly and disconnect solar array modules to the battery pack [8]. Using this, the whole capacity of battery is likely unreachable. To alleviate this problem and avoid overheating, an alternative charging method based on on-off control is employed in [9]. In this way, the energy stored in solar PV array modules is not used up, and energy utilization is severely compromised during the off time. Another method which is proposed is based on State of Charge (SOC) using estimator [7]. However, the main deficiency is that a reliable estimation of the State of the Charge (SOC) is difficult due to battery limit models and uncertainty in its parameters.

In recent decades, Dynamic FACTS, Switched LC Compensators, Active Power Filters (APF), and FACTS switched filter compensators devices have been proposed to eliminate line current harmonics, improve power factor, and increase power quality [10]. Accordingly, chances are these devices can modify power factor and harmonic distortion in smart grids and battery charging systems. A FACTS-based AC-DC hybrid filter compensator is developed by the Second Author and proposed for EV and Hybrid Plug-in vehicles. The low cost FACTS-based device developed by the Second Author is controlled by a multi-loop dynamic error-driven and weighted modified PID controller, in order to achieve the best battery charging performance. Another multi-loop error-driven controller is also used to control Buck-Boost DC-DC chopper. Digital simulation is used to compare the dynamic operation of the mobile/EV battery charger without and with FACTS-based filter compensation device for power factor correction, harmonic reduction, power quality improvement, and minimal inrush current conditions on both AC and DC sides.

2. Proposed Scheme for Battery Charging Grid

Considering the fact that in the basic scheme for a battery charging V2G system (Fig. 1) power factor is considered low, a new controller is designed to improve power factor and stabilize voltage. To achieve this aim, firstly the DC-DC chopper is replaced by a Buck-Boost DC-DC converter, and then the basic controller used for DC-DC chopper producing on-off sequence switching is revised to function better than normal constant voltage/constant current chargers.

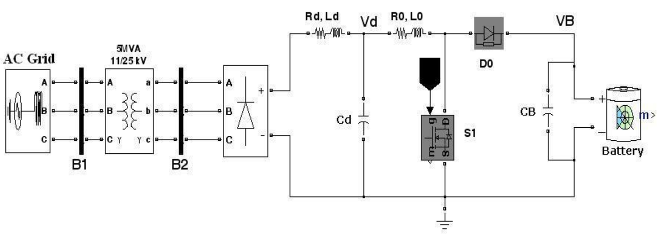
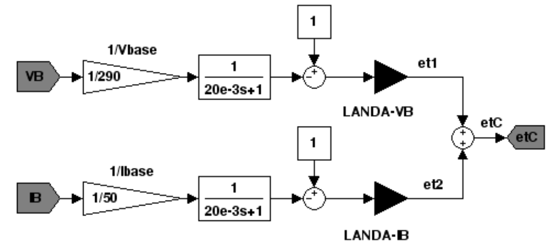


Fig. 1. Basic V2G battery charging modified with boost DC chopper scheme.

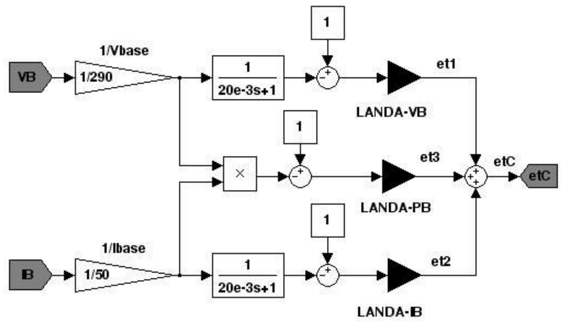
2.1. Tri-loop Error Driven Controller for DC-DC Chopper

In the basic battery charger, DC-DC converter is controlled by a dual-loop error driven controller which is shown in Fig. 2a. However, the modified controller for pulse width switching of DC-DC Buck-Boost chopper in the proposed battery charger is a dynamic tri-loop error driver using error value of voltage, current, and power at the node "b". The controller is a slightly mode to calculate the differences between voltage, current, and instant power and their specified reference values. In fact, the third new loop which is introduced in this scheme is the loop which computes error of power at node "b". This controller is shown in Fig. 2.b which now combines three weighted voltage, current, and power tracking loops.

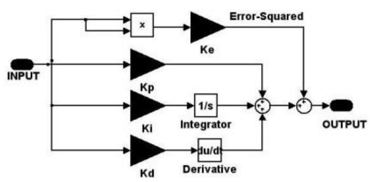
In addition to tri-loop dynamic error driven controller, PID controller is modified by an error squared acceleration loop for fast dynamic response. Therefore, the output of the tri-loop controller (etC) is sent to a weighted modified PID (WM-PID) controller (Fig 2.c).



(a)



(b)



(c)

Fig. 2.(a) Old dual-loop controller (b) New tri-loop error driven controller for Buck-Boost DC-DC chopper (c) Weighted Modified PID.

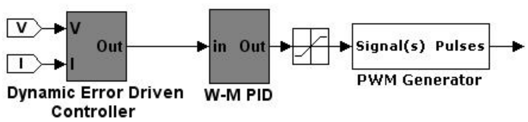


Fig. 3. Overall diagram of the controller.

Considering the proposed tri-loop controller and the overall diagram shown in Fig. 3, following equations describe the controller:

$$et1_C(k) = \gamma_{VB}\left(V_{B-ref} - V_{B-pu}(k)\left(\frac{1}{1+0.02S}\right)\right) \quad (1)$$

$$et2_C(k) = \gamma_{IB}\left(I_{B-ref} - I_{B-pu}(k)\left(\frac{1}{1+0.02S}\right)\right) \quad (2)$$

$$et3_C(k) = \gamma_{PB}\left(P_{B-ref} - P_{B-pu}(k)\right) \quad (3)$$

$$etC(k) = et1_C(k) + et2_C(k) + et3_C(k) \quad (4)$$

2.2. Hybrid FACTS-Based Devices Mounted at The Node d

In order to stabilize voltage profile at node d, a new hybrid FACTS-based (NPSFC+GPFC) the type of which is Green Plug Filter Compensator (GPFC) is designed (Fig. 4). GPFC consists of two capacitors on DC side of a rectifier bridge. Performance of GPFC is determined by an IGBT/MOSFET switch (S2) which is located on DC side of the rectifier bridge.

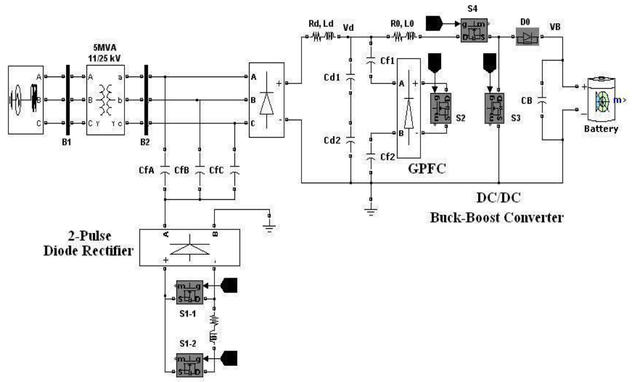


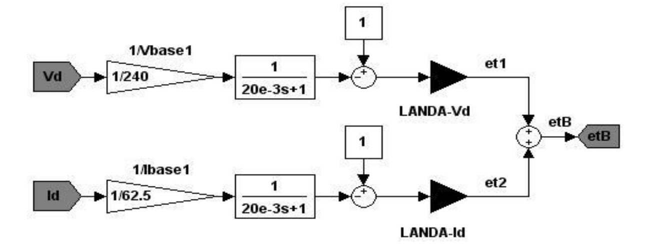
Fig. 4. Proposed FACTS battery charging scheme V2G with hybrid FACTS (NPSFC+GPFC) scheme.

To produce different operating states, on-off pulses for the switch are manipulated by the tri-loop dynamic error driven controller developed by Second Author (Fig. 5a). Input signals of the controller are voltage and current of node d. The first loop extracts error between per unit value of the voltage at node d and its reference value (et1). The second loop tracks the power to mitigate its ripples (et2). Finally, the third loop calculates error between per unit value of current at node d and its reference value (et3). Weighted values of the three errors are added together, and the result (etB) is sent to the WM-PID controller. Output signal of WM-PID is utilized by PWM generator to produce on-off switching pulses for switch S2.

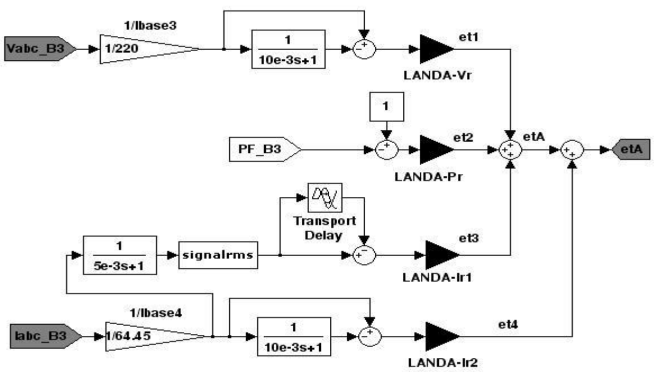
2.3. *New FACTS-Based Device Mounted at Bus B2*

In order to stabilize the common AC and DC bus voltages and increase power factor, a Neutral Point Switching Filter Compensator (NPSFC) is used at Bus B2. Its structure encompasses three capacitors each of which is connected between one of the three phases of the network and terminal A of a rectifier bridge (Fig. 4). On the DC side of the rectifier, an RL branch is connected. Terminal B of the rectifier is grounded. Using two IGBT/MOSFET switches (S1-1, S1-2), two different modes are defined for NPSFC. If S1-1 is close (and S1-2 is open), NPSFC FACTS device is like an Active Power Filter (APF). If S1-2 is close (S1-1 is open), it behaviours as a power factor compensator.

In order to satisfy the practical performance of both different modes of NPSFC, a quad-loop dynamic error driven controller is designed, and it is shown in Fig. 5b. In fact, this controller handles on-off sequences of S1-1 and S1-2. Voltage, current, and power factor of bus B2 are input signals of this controller. The controller is a combination of four loops which their values are added together. The first loop (et1) and third (et3) loop calculate dynamic voltage and RMS current errors, respectively. The second loop computes difference between power factor at bus B2 and its desired value. Finally, the fourth loop is regulating the dynamic current error at bus B2. All the values of scaling and time delay of the controller were selected by an offline guided trial and error method to insure fast response and minimum total error (etA) [11]. Output signal of this controller (etA) is sent to the WM-PID and then to PWM signal generator to yield switching pulses for switches S1-1 and S1-2.



(a)



(b)

Fig. 5. (a) Tri-loop dynamic controller for MOSFET switch S2 (b) Quad-loop controller for complementary MOSFET switches S1-1 and S1-2.

In accordance with the overall diagram already shown in Fig. 3 and Fig. 5a, following equations are mathematical function of the dual-loop controller of the GPFC device:

$$et1_B(k) = \gamma_{Vd}\left(V_{d-ref} - V_{d-pu}(k)\left(\frac{1}{1+0.02S}\right)\right) \quad (5)$$

$$et2_B(k) = \gamma_{Id}\left(I_{d-ref} - I_{d-pu}(k)\left(\frac{1}{1+0.02S}\right)\right) \quad (6)$$

$$etB(k) = et1_d(k) + et2_d(k) \quad (7)$$

The same equations are extracted for the quad-loop controller:

$$et1_A(k) = \gamma_{Vr}\left(V_{r-ref}(k) - V_{r-pu}(k)\left(\frac{1}{1+0.01S}\right)\right) \quad (8)$$

$$et2_A(k) = \gamma_{PFr}\left(PF_{r-ref} - PF_{r-pu}(k)\right) \quad (9)$$

$$et3_A(k) = \gamma_{Ir1}\left(RMS\left(I_{r-pu}(k)\left(\frac{1}{1+0.005S}\right)\right) - I_{r-pu}(k)\left(\frac{1}{1+0.005S}\right)\left(\frac{1}{1+SD}\right)\right) \quad (10)$$

$$et4_A(k) = \gamma_{Ir2}\left(I_{r-pu}(k) - I_{r-pu}(k)\left(\frac{1}{1+0.01S}\right)\right) \quad (11)$$

$$etA(k) = et1_A(k) + et2_A(k) + et3_A(k) + et4_A(k) \quad (12)$$

In all of the three proposed controllers, the output signal of the WM-PID controller is calculated as:

$$Output_{WM-PID}(t) = K_e etX(t)^2 + K_P etX(t) + K_I \int etX(t) + K_D \frac{detX(t)}{dt} \quad (13)$$

3. Lithium-Ion Battery

Lithium-Ion battery is a rechargeable battery that can provide high energy density, and it is efficient, reliable, and appropriate for both high energy and low energy applications. For example, in high-energy applications, Li-ion battery can be used in linear generator system, backup power system, and hybrid electric vehicle system. However, in low power applications, Li-ion battery is primarily used in the industry of information and communication technology due to the need for high capacity, long shelf life, light weight, and small dimensions. These facts make the battery becoming the best choice to support most of today's electronic portable applications. Also, it can be found clearly in many electronic equipment because of its potential ability over the other batteries. However, Li-ion battery charging is more complicated since many factors should be considered especially when the battery pack consists of a number of Li-ion battery cells, which are connected in series. Moreover, the battery cannot be over charged for its chemistry limitations. Therefore, exceptional control unit is required, and this unit plays an important role in controlling both charging and discharging processes to ensure that Li-ion battery pack is long-lasting or extended life [12].

3.1. Charging Mode

The battery charging behaviour is particular at the end of the charge (EOC) characteristic, which is different and depends on the battery type. The Li -Ion and Lead-Acid batteries have the same EOC features since the voltage increases quickly when the battery gets the full charge. This fact is modelled by the polarization resistance term. In the charge method, the polarization resistance rises until the battery is almost fully charged (it = 0). Above this point, the polarization resistance increases shortly. As an alternative to the polarization resistance of the discharge model, the polarization resistance is now given by:

$$PolarizationResistance = K\frac{Q}{it} \quad (14)$$

Theoretically, when it = 0 (fully charged), the polarization resistance is infinite. This is not exactly the case in practice. Indeed, experimental results have shown that the contribution of the polarization resistance is shifted by about to:

$$PolarizationResistance = K\frac{Q}{it-0.1Q} \quad (15)$$

Similar to the discharge model, the exponential voltage for the Li -Ion Battery is the A exp(−B it) term [13][14].

4. Digital Simulation Results

In this section, effectiveness of the novel hybrid FACTS-based (NPSFC+GPFC) scheme for battery charging V2G is validated using MATLAB/SIMULINK toolbox. Through dynamic simulation, a 3-phase short circuit is applied at 0.1 sec on the AC side of the 3-arm rectifier of the AC grid, and it is cleared after 0.05 sec. All parameters of the elements which are used in simulation are mentioned in table. 1. Results of the dynamic simulation are displayed through Fig. 6 to Fig. 12. It is apparently visible that V2G scheme with the hybrid FACTS devices has stabilized voltages, increased power factor value, and reduced inrush currents.

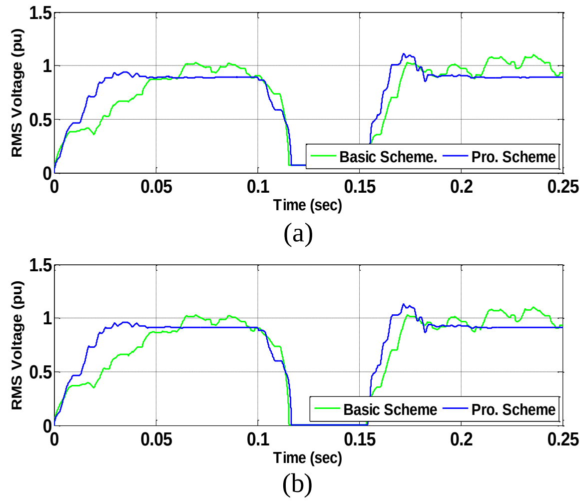


Fig. 6. (a) RMS Voltage (pu) of bus B1 (b) RMS Voltage (pu) of bus B2.

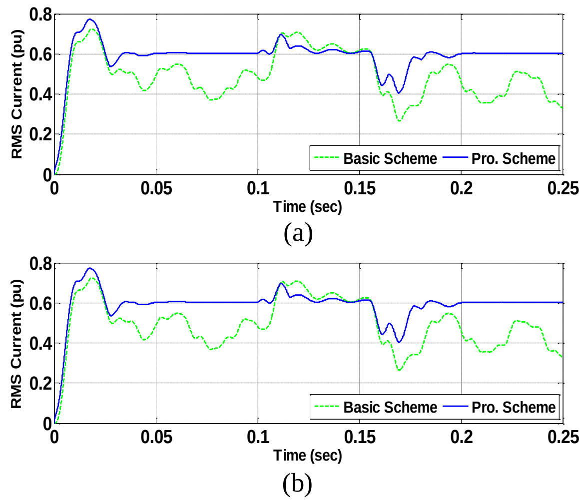


Fig. 7. (a) RMS Current (pu) of bus B1 (b) RMS Current (pu) of bus B2.

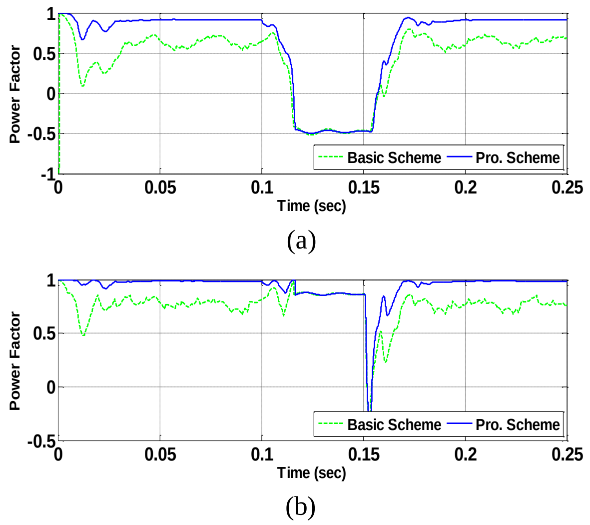


Fig. 8. (a) Power Factor of bus B1 (b) Power Factor of bus B2.

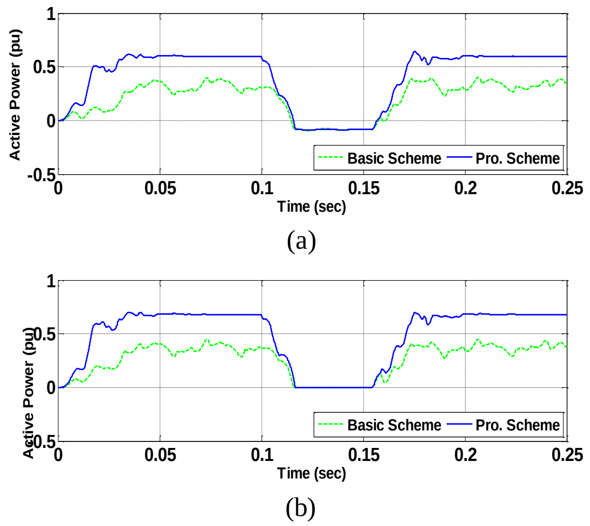


Fig. 9. (a) Active Power of bus B1 (b) Active Power of bus B2.

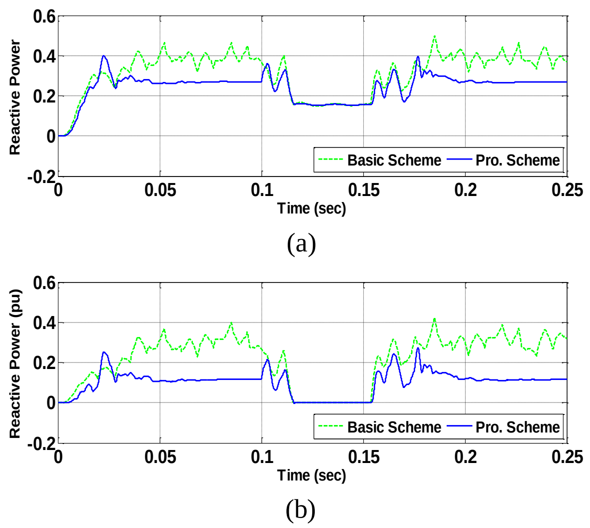


Fig. 10. (a) Reactive Power of bus B1 (b) Reactive Power of bus B2.

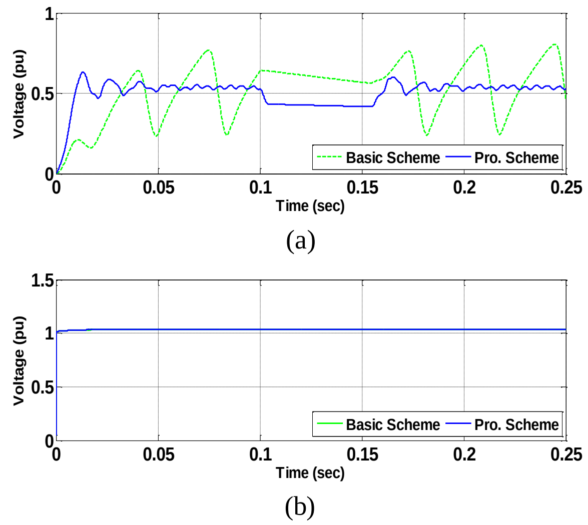


Fig. 11. (a) Voltage (pu) at node d (b) Voltage (pu) at node b.

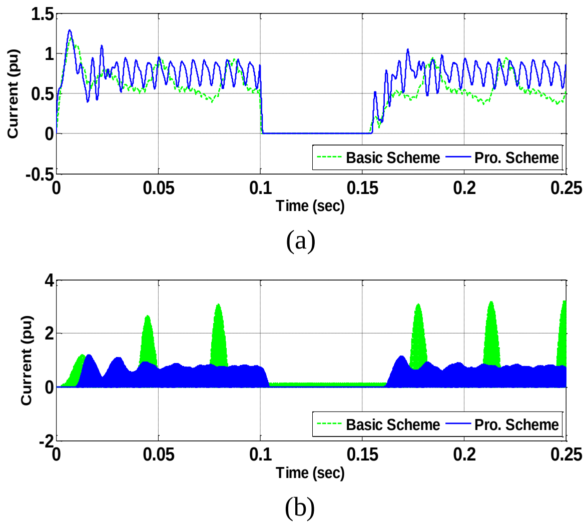


Fig. 12. (a) Current (pu) at node d (b) Current (pu) at node b.

5. Conclusion and Extensions

A novel hybrid FACTS-based AC-DC Neutral Point Switched Filter Compensation (NPSFC) Filter Compensator scheme developed by the Second Author is validated in order to improve power quality for future V2G battery charging stations. The dynamic multi-loop error-driven weighted modified PID controllers are used for switching of the NPSFC plus GPFC FACTS-based devices and the DC-DC buck-boost chopper. Hybrid NPSFC+GPFC device is effective in reducing harmonics, decreasing transient inrush currents, stabilizing AC and DC side voltages, improving power factor, and enhancing power quality and battery charger performance. Fast dynamic performance can be achieved using a dynamic gain error squared supplementary loop that improves fast charging and reduces the transients in both AC and DC sides.

The same FACTS scheme is being tested for hybrid renewable Energy AC-DC Microgrid-PV-Fuel Cell AC-DC interface scheme for Village Electricity.

Appendix A.

Table 1. Parameters of the battery charging system

Device	Value
Battery	Lithium-Ion, 300V, 650Ah, S.O.C 10%
AC Grid	50 MVA, X/R=5,Vbase=11 KV
Power Transformer	11/0.22KV, 50 KVA, 60 Hz
C_{fA}, C_{fB}, C_{fC}	90 Micro Farad
C_{d1}, C_{d2}, C_B	4500 Micro Farad
C_{f1}, C_{f2}	2500 Micro Farad

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