

ON BOARD V2G INTEGRATOR: AN ARCHITECTURE FRAMEWORK FOR EV INTEGRATION TO GRID

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Abstract— Vehicle to Grid (V2G) is concept of connecting group of electric vehicles (EV) to the grid for power transaction. EVs can be connected to the grid through home interface or through the chargers available at charging stations. In this paper a single phase on board charger with low complexity control scheme is proposed for EV power transaction. The power flow from and to the grid is processed using two stage cascaded converters consisting of a bidirectional DC-DC and DC-AC converters. The LCL filter is used as interface between DC-AC converter and the grid to attenuate the grid current harmonics. A proportional-resonant (PR) controller is employed for the control of grid current and to enable the unity power factor operation of the DC-AC converter. The setbacks associated with conventional proportional integral (PI) controller for single phase system is elevated by employing PR controller. Filter design guidelines and the control strategy developed for the proposed system is numerically simulated and verified with extensive simulation carried using MATLAB/SIMULINK. The results demonstrating the feasibility and viability of the proposed system are presented.

Key words— Vehicle-to-Grid(V2G), V2G Integrators, On board charger.

1. INTRODUCTION

The growing oil demand and carbon emissions have inspired the governments, car manufactures and the environmentalist to promote the manufacturing of EV. EVs will gradually replace the other existing contemporary vehicles. EVs can be connected to the grid for power transaction. A single EV can consume but cannot deliver power to the grid. The group of EVs makes a sizeable difference and delivers power to the grid. The concept of connecting group of EVs to the grid is called V2G. V2G plays a prominent role in fulfilling the grid requirements and meet the load demand. EVs also support the ancillary services like load levelling, voltage regulation, frequency regulation and balancing. EVs need bidirectional charger to sell or buy power from the grid. Further the bidirectional charger has the direct current (dc) link capacitor which is inherently able to provide the reactive power support to the power grid. The state of charge (SOC) of the EV battery plays a key role in V2G operation and promotes the concept of Vehicle-to-Home (V2H), Vehicle-to-Vehicle (V2V) and V2G [1]. The architectural and conceptual framework of V2G is shown in Fig. 1. The EV can be connected to the home grid or other interface using

the On-Board or Off-Board bidirectional charger or V2G integrators.

The power flow from and to the grid is processed using two stage cascaded converters consisting of a bidirectional DC-DC and DC-AC converters. The LCL filter is used as an interface between DC-AC converter and the grid to attenuate

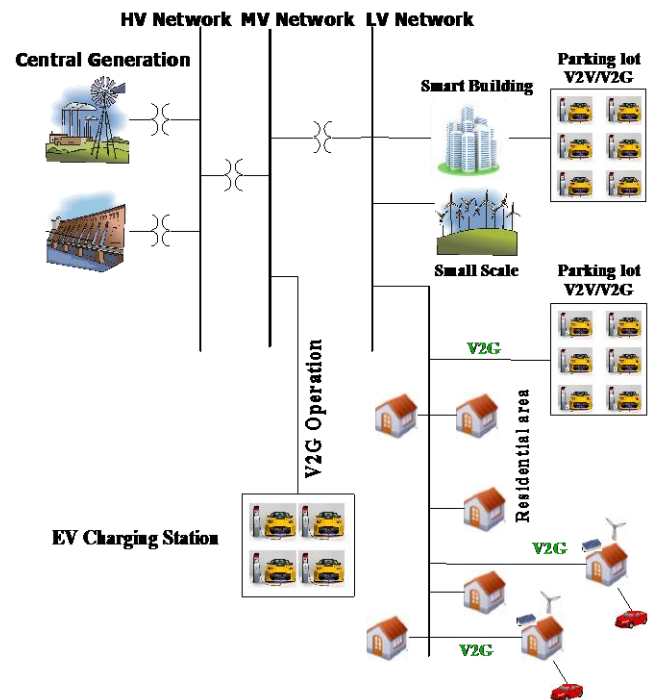


Fig. 1. Conceptual Framework of V2G.

the grid current harmonics. A proportional-resonant (PR) controller is employed for the control of grid current and to enable the unity power factor operation of the DC-AC converter. The setbacks associated with conventional proportional integral (PI) controller for single phase system is elevated by employing PR controller.

The various opportunities and challenges of V2G are articulated in [1] and the existing techniques available for integration are reviewed in [2] and the potential economic benefits of V2G are listed. Willett Kempton, Jasna Tomic are pioneers of the V2G concept and their research articles are

serving as base papers for the researchers in this area. In the year 2005 they articulated two papers: first briefed the basics of V2G and the revenue generation associated with it [3] and in the second paper they explained the complexities involved in implementation of V2G [4]. The potential benefit and sustainability of V2G in Smart Grid Environment is discussed in [5] and the detailed conceptual frame work of V2G is presented in [6]. The impact of V2G on distribution grid is discussed in [7] and the experimental verification and difficulties of V2G are expressed in [8]. The contactless charger suitable for Indian Power Grid environment and benefits are projected in [9] and requirements of bidirectional charger for V2G is discussed in [10]. The new approach to V2G connection is proposed in [11] and economic opportunities related to V2G aspect is presented in [12].

The power electronic interface for the power transaction from V2G and G2V may involve one or more stages. Most of the EV chargers are of conductive type, where there is an electrical contact between vehicle and the utility. Bidirectional converter topologies are to be used chargers for V2G operation. In addition to traction batteries the auxiliary battery used for lighting, wipers needs to be charged. A reconfigurable battery charger in which the auxiliary battery is charged by the main traction battery is proposed in [13].

In this paper an architectural framework of On-board V2G integrator is proposed. A single phase on board charger with low complexity control scheme is presented for EV power transaction. The system designed is also suitable for V2H as the charger considered is designed for voltage rating of 230 V. The DC-AC bidirectional converter is made to operate at unity power factor injecting or drawing the grid current with low harmonic distortion. The control scheme employed consists of a PR controller for grid current control as an alternative to the widely used PI controller for both V2G and G2V operation [14]. The low gain of PI controller at grid frequency leads to steady state error and also the limited bandwidth hinders the response time. The DC-DC converter employed has both the capability of stepping up (boost) the dc link voltage during V2G operation and stepping down (buck) the dc link voltage during G2V operation in comparison to battery voltage.

2. ON-BOARD V2G INTEGRATOR

Fig.2 shows the topology diagram of the proposed system consisting of cascaded power converters. It consists of two power stages. The first stage is bidirectional DC-DC converter and the second stage is a bidirectional DC-AC converter. The direction of power flow is dictated by the operating mode. The active power flows from the batteries to the dc link and then to the grid during V2G mode of operation and in the opposite direction during G2V mode of operation.

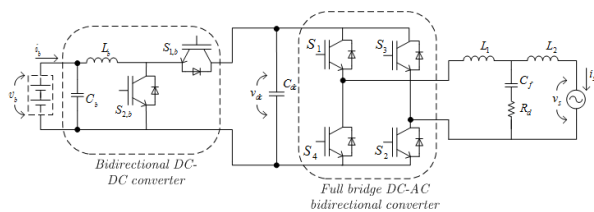


Fig. 2. Topology of the proposed on board charger.

A. Grid to vehicle (G2V) mode of operation

In this mode of operation the DC-AC bidirectional converter acts as an active rectifier drawing sinusoidal current from the grid in phase with the grid voltage. The bidirectional DC-DC converter operates as a buck converter in current control mode.

i) Three level bidirectional DC-AC converter control

In grid connected operation, converter operates in current controlled mode as the voltage across it is maintained by the infinite grid. Thus for proper operation, synchronization with the grid voltage is mandatory. This is achieved using a phase locked loop (PLL) which generates an in phase component of the grid voltage and eliminates any harmonics present. An LCL filter acting as an interface between the DC-AC converter and the grid reduces the harmonic distortion in the grid current being injected. As the filter is of order three, the amount of attenuation provided over high frequency range is more even with smaller value of passive components. However the filter poses a significant problem due to its low or zero impedance at the resonant frequencies makes the design of current controller complicated. A general approach to damp the resonance oscillations is to add a damping resistor in series with the filter capacitor. Even though the method seems to be effective in stabilizing the overall filter characteristics, it suffers from the increased power loss.

As an alternative to passive damping, approach to introduce the same effect using feedback of the parameters which can serve as damping term known as active damping. Bode plot of LCL filter for various value of damping is shown in Fig.3. For an application with a stiff grid, a passive damping method is often preferred for its simplicity and low cost. The control of DC-AC converter is achieved through two loops with outer loop as voltage control loop and with inner loop as current control loop. The block diagram of the LCL filter with the inner current loop is shown in Fig.4. Various controllers like stationary frame control, dq frame control and *abc* frame controllers are employed to maintain the grid current to be sinusoidal with lower harmonic distortion.

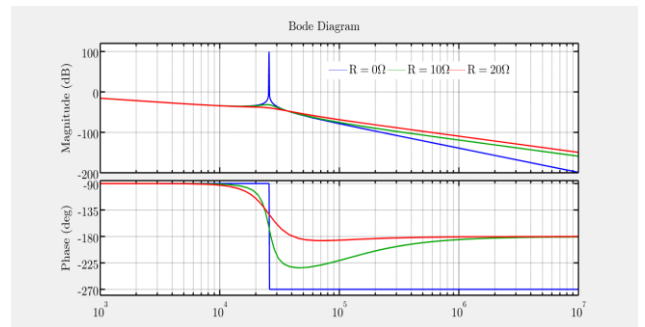


Fig. 3. Bode diagram of LCL filter.

In this paper a proportional resonant (PR) compensator is used to track a sinusoidal current reference signal with zero steady state error as the controller introduces an infinite gain theoretically at the grid frequency.

The expression for grid current from the above block diagram can be obtained as

$$I_g(s) = G_p(s) \left(\frac{s^2 L_1 C_d + s C_d R_d + 1}{s C_d R_d + 1} V_g - V_{inv} \right) \quad (4)$$

As, the magnitude and phase response of $\frac{s^2 L_1 C_d + s C_d R_d + 1}{s C_d R_d + 1}$

are 0 dB and 0° at the fundamental frequency of the grid. Therefore, equation (4) can be simplified to equation

$$I_g(s) = G_c(s) (V_{inv} - V_g) \quad (5)$$

the relationship between the input and the output of the current loop can be derived as:

$$I_g(s) = H_1(s) \cdot I_g^*(s) + H_2(s) \cdot V_g(s) \quad (6)$$

To successfully track the $i_g^*(t)$ signal without steady state errors, the magnitude of $H_1(j\omega)$ in equation (6) has to be

equal to 1 at the fundamental frequency of $i_g^*(t)$. Thus, it is

clear that if $G_c(j\omega)$ has infinite gain at fundamental

frequency, $H_1(j\omega)$ would have a unity gain. The control structure of a PR controller is given in equation (5).

$$G_c(s) = K_p + \frac{K_i \cdot 2 \cdot \xi \cdot \omega_o \cdot s}{s^2 + 2 \cdot \xi \cdot \omega_o \cdot s + \omega_o^2} \quad (7)$$

where $\omega_o = 2\pi f_o$, K_i is the fundamental harmonic gain, and ξ is the damping factor.

The bode diagram for the uncompensated and compensated current control loop is shown in Fig.5. It can be seen that after compensation the overall bandwidth of the system is increased which makes the system to respond faster. The gain of around 82 dB at the grid frequency (50 Hz) leads to zero steady state error in tracking of the reference current generated. The overall control structure with outer voltage loop embedded is shown in Fig.6. The converter DC link voltage

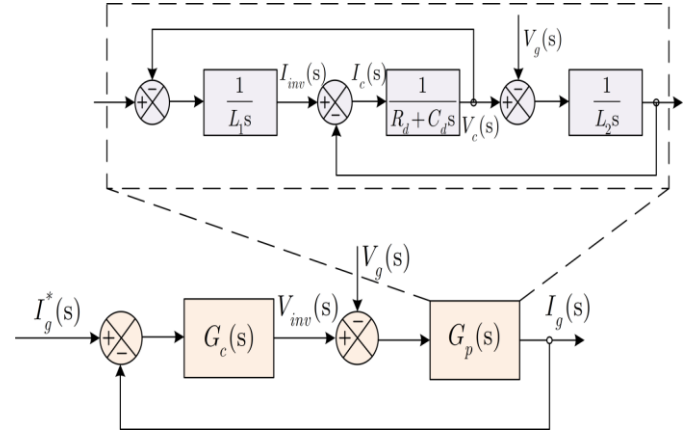


Fig. 4. Block diagram of LCL filter.

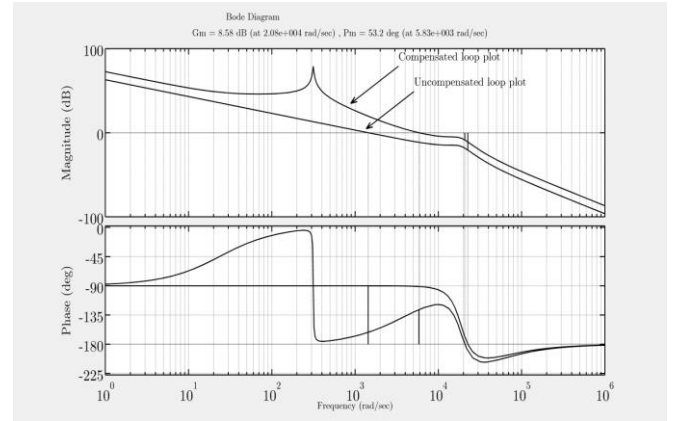


Fig. 5. Bode diagram of uncompensated and compensated current control loop

should be greater than peak value of the grid voltage, so that the power can be transferred from EVs to grid. Assuming that the sinusoidal current is being pumped to the grid, the DC link voltage will have a second harmonic component. This leads to control system instability if it is not filtered out before using for control purpose. Thus, band stop filter (BSF) is used to remove 100 Hz component in V_{dc} . The unipolar pulse width modulation scheme is employed for gating the power switches.

ii) Bidirectional DC-DC Converter Control

The dc link voltage is maintained constant by the DC-AC converter and the DC-DC converter acts as a buck converter during this mode (G2V). The control structure for accomplishing this is shown in Figure 7. As per the recommendation by the EV manufacturer generally a constant current charging is done first till the battery voltage reaches the recommended maximum value and then followed by a constant voltage charging. A proportional integral controller

B. Vehicle to Grid (V2G) mode of operation

Table 1 Specification of the Proposed On Board Charger

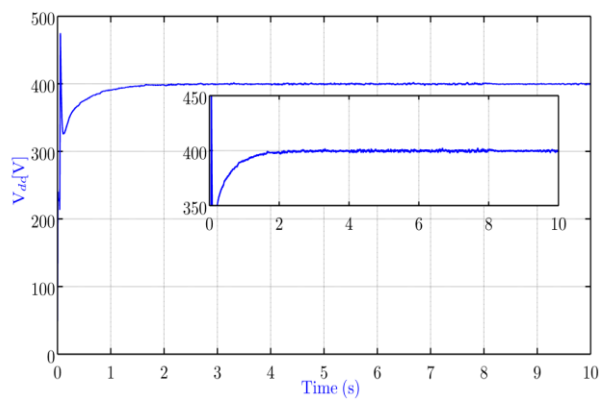
<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Grid voltage (RMS)	230	V
Grid frequency	50	Hz
Maximum input current (RMS)	35	A
Maximum input power	8	KVA
Output voltage range (DC)	190-270	V
Maximum output current (DC)	30	A
Inductor L_1	0.3	mH

Inductor L_2	0.5	mH
Capacitor C_f	2	μF
Capacitor C_b	800	μF
Capacitor C_{dc}	1000	μF
Switching frequency of DC-AC converter	10	kHz
Switching frequency of DC-DC converter	25	kHz

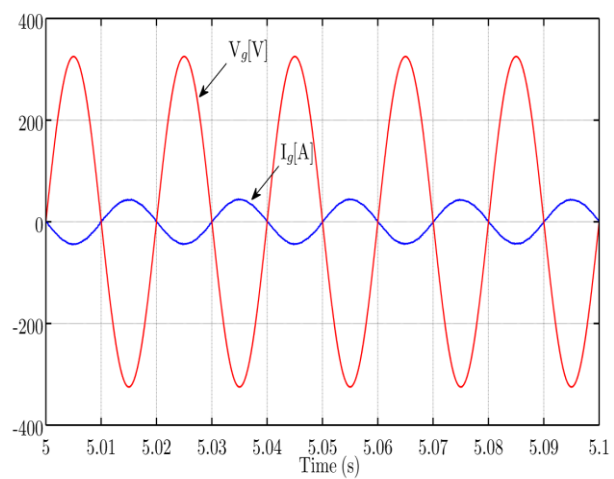
	K_P	K_I
PI controller 1	0.3	2
PI controller 2	0.75	5
PR controller	3	10000

To demonstrate and validate the feasibility of on board integrator, simulation were carried out using MATLAB/SIMULINK with the parameters shown in Table I and II respectively. Fig.7 shows some of the waveforms corresponding to G2V operation. Fig.7(a) shows the dc link voltage waveform being regulated at 400 V.

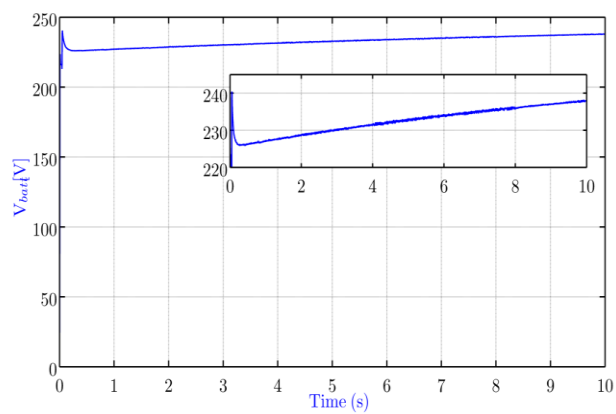
Fig. 8(a-b-c) shows the regulated dc link voltage, battery voltage and the battery current during V2G operation. The bidirectional dc-dc converter acts as a boost converter during this mode. Fig. 8(d) shows the grid voltage and the sinusoidal current being injected to the grid. It can be seen that the current injected is in phase with the grid voltage ensuring the unity power factor operation. The battery is supplied with a constant active power ($P = 6 \text{ kW}$) and zero reactive power ($Q = 0$) as shown in Fig. 8(e). The harmonic level in the grid current being drawn is found to be 2%. The harmonic spectrum of the grid current is shown in Fig. 8 (f).



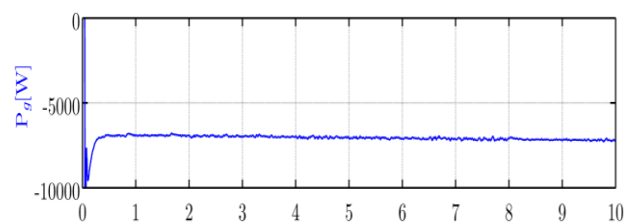
(a)



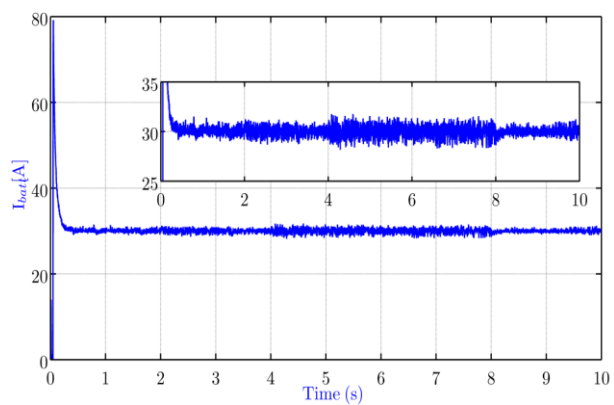
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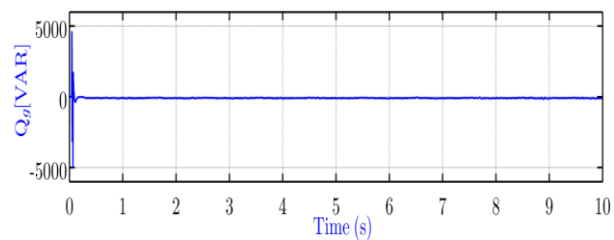
(b)

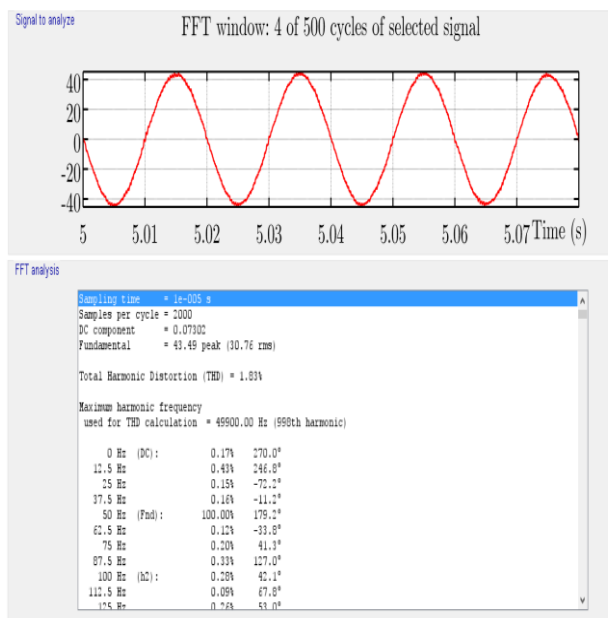


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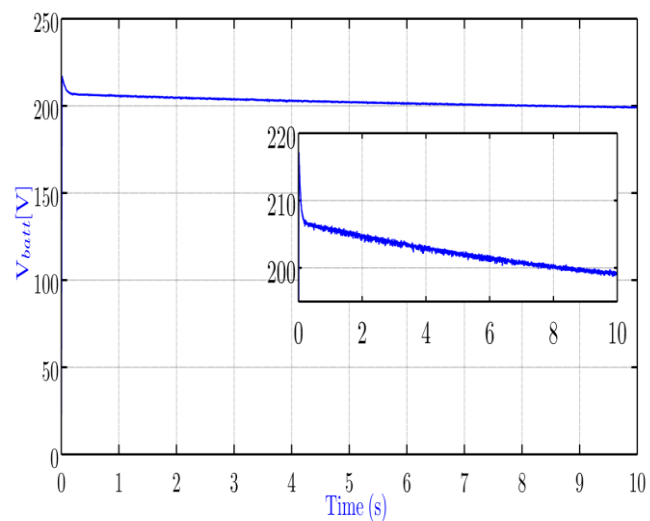


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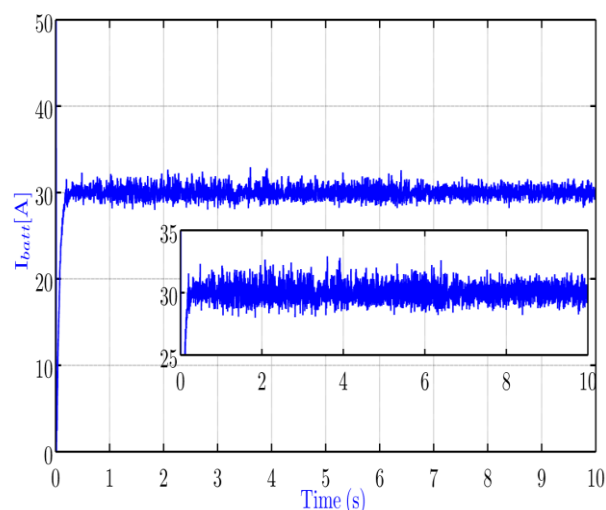




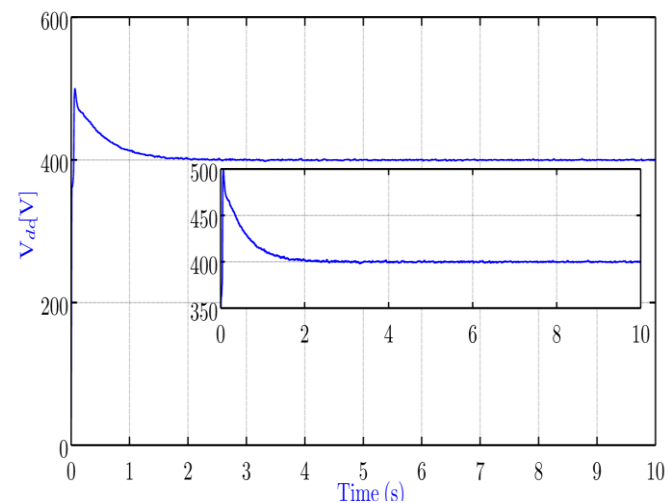
(f)



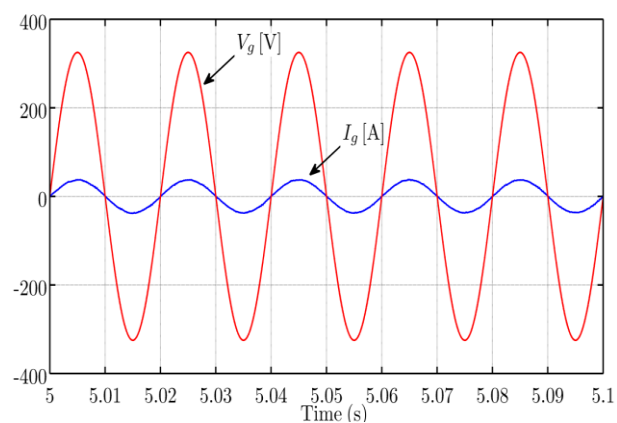
(b)



(c)



(a)

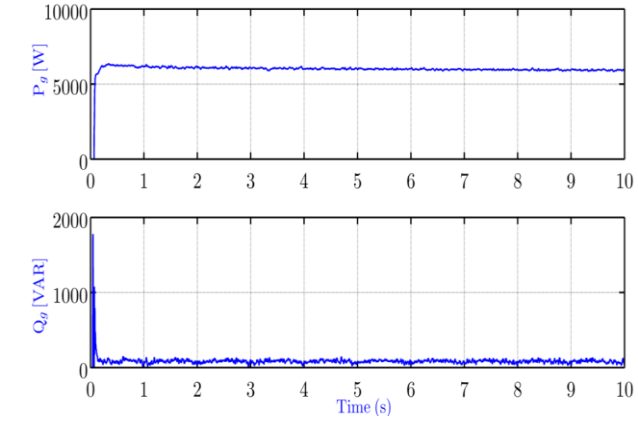


(d)

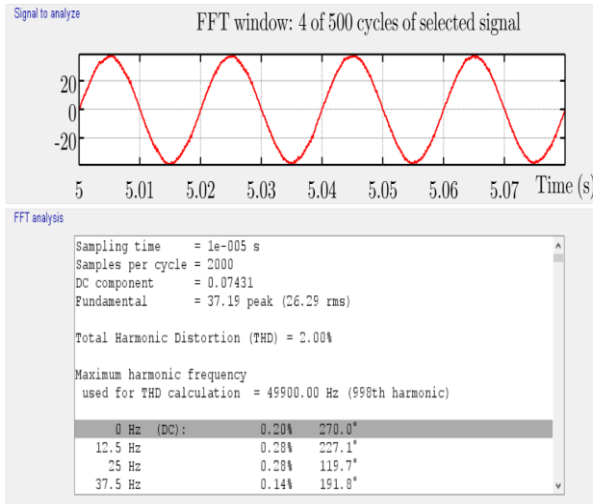
Fig. 7. Operating waveforms during V2G operation (a) DC link voltage (b) Battery voltage (c) Battery current (d) Grid voltage and current (e) Active and reactive power (f) Harmonic spectrum of grid current (1.83% THD).

REFERENCES

- [1] C. Liu, K., Chau, D., Wu., S. Gao.: Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies. In: Proceedings of the IEEE, 101(2013), p. 2409–2427.
- [2] M. Yilmaz., P. T. Krein.: Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces. In: IEEE Transactions on Power Electronics, 28(2013), p.5673–5689.
- [3] W. Kempton., J. Tomić.: Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. Elsevier Journal of power sources, 144(2005),p. 268–279.
- [4] W. Kempton., J. Tomić.: Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. In: Elsevier Journal of Power Sources, 144(2005), p.280–294.
- [5] D. Dallinger, J. Link., M. B'uttner.: Smart grid agent: Plug-in electric vehicle Tech. Rep. Sustainability and Innovation, (2013).
- [6] C. Guille., G. Gross.: A conceptual framework for the vehicle-to-grid (V2G) implementation. In: Elsevier Energy policy, 37(2009), p.4379–4390.
- [7] R. C. Green., L. Wang., M. Alam.: The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook. In: Elsevier Renewable and Sustainable Energy Reviews, 15(2011),p.544–553.
- [8] P. Mendoza-Araya., P. Kollmeyer., D. Ludois.: V2G integration and experimental demonstration on a lab-scale microgrid. In: Proceedings of the Energy Conversion Congress and Exposition (ECCE), 2013 pp. 5165–5172.
- [9] K. Thirugnanam., T. E. R. Joy., M. Singh., P. Kumar.: Modeling and control of contactless based smart charging station in V2G scenario. In: IEEE Transactions on Smart Grid 5(2014), p.337–348.
- [10] M. A. Khan., I. Husain., Y. Sozer.: A bi-directional dc-dc converter with overlapping input and output voltage ranges and vehicle to grid energy transfer capability. In: Proceedings of IEEE International Electric Vehicle Conference (IEVC), 2012, p. 1–7.
- [11] K.D. Kim., Y.-H., J.-G. Kim., Y.-C. Jung., C.-Y. Won.: Novel high efficiency bidirectional converter using power sharing method for V2G. In: IEEE Proceedings Vehicle Power and Propulsion Conference, 2012.
- [12] H. R. Esmailian., M. M. H. Bioki., M. Rashidinejad., M. Shojae.: Techno-economical evaluation of evs parking lot construction by distribution companies. In: IET Integration of Renewables into the Distribution Grid (CIRED), (2012), p. 1–4.
- [13] J. Pinto., V. Monteiro., H. Gonçalves., J. L. Afonso.: Onboard reconfigurable battery charger for electric vehicles with traction-to-auxiliary mode. In: IEEE Transactions on Vehicular Technology, 63(2014), p.1104–1116.
- [14] R. Teodorescu., F. Blaabjerg., M. Liserre., P. C. Loh.: Proportional-resonant controllers and filters for grid-connected voltage-source converters. In: IEE Proceedings on Electric Power Applications, 153(2006), p.750–762.
- [15] J. Mo.: Performance modeling of communication networks with markov chains. Synthesis Lectures on Data Management 3(2010), p.1–90.
- [16] S. Kumar., U. R. Yaragatti.: Development of markov chain-based queuing model and wireless infrastructure for ev to smart meter communication in V2G. In: DeGruyter International Journal of Emerging Electric Power Systems, 16(2015), p.153–163.
- [17] S. Kumar., U. R. Yaragatti., S. Manasani.: Modeling and architectural frame work of off-board V2G integrator for smart grid. In: International Journal of Renewable Energy Research (IJRER) 4(2014), 831–836.



(e)



(f)

Fig. 8. Operating waveforms during G2V operation (a) DC link voltage (b) Battery voltage (c) Battery current (d) Grid voltage and current (e) Active and reactive power (f) Harmonic spectrum of grid current (2% THD).

4. CONCLUSION

A low complexity onboard charger for EVs has been presented. The proposed system allows the integration of EV battery to the grid through power processing stages. The power flows from vehicle battery to grid during V2G and from grid to vehicle during G2V mode of operation. The grid current being injected/absorbed is maintained to have a power factor of unity and low harmonic distortion. Design details of the current controller are discussed and extensive simulation results demonstrating both the operating modes are presented. Simulation is carried out using MATLAB/SIMULINK platform and the result showing the harmonic analysis of the grid current is found to be within the prescribed power quality limits of IEEE.