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A New Battery Charger for Plug-in Hybrid Electric Vehicle Application using Back to Back Converter in a Utility Connected Micro-grid

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***Abstract*—The major drawbacks of the most battery chargers for plug-in hybrid electric vehicle (PHEV) are high volume and weight, low power, long charging time, deleterious harmonic effects on the electric utility distribution systems and low flexibility and reliability. This paper proposes a new battery charger structure for PHEV application using back to back (B2B) converter in a utility connected micro-grid. In the proposed structure, an AC micro-grid, based on the typical household circuitry configuration, is connected to the grid via a B2B converter; and the DC link is used for battery charging. In fact, the B2B converter can provide an isolated, low cost, simple and reliable connection with power-flow management between the grid, micro-grid and battery. This proposed structure, depending on the power requirement of the vehicle, can run in four different modes: battery charging mode from the grid (G2V) or micro-grid (M2V), vehicle to grid mode (V2G) and vehicle to micro-grid mode (V2H). The feasibility of the proposed scheme has been validated in the simulation study for various operating conditions.**

***Index Terms*—AC micro-grid, Back to back converter, Battery charger, PHEV application.**

I. Introduction

PLUG-IN hybrid electric vehicles (PHEV) have attracted a lot of attention for researchers these days due to their attractive properties such as their reduced fuel usage and greenhouse emissions. PHEVs have the advantage of a long driving range since fuel provides a secondary resource [1 and 2]. In fact, PHEV is a hybrid electric vehicle that uses rechargeable batteries that can be recharged by plugging it in to an external source of electric power.

In PHEVs, a power electronic converter, called battery charger, is utilized to regulate the supplied power by the electric utility or distributed generation (DG) for recharging the battery pack. Battery Charger systems are classified into the off-board and on-board types with unidirectional or bi-directional power flow. A typical battery charger has two main stages, as shown in Fig. 1: a grid-connected AC–DC converter and a DC–DC converter to regulate battery current [3].

Recently, bi-directional battery chargers are used to operate the PHEV as a DG to supply power to the grid or micro-grids [4-7]. As a result, connection to the grid or micro-grid allows opportunities such as ancillary services, flexibility, reliability, tracking the output of renewable energy sources, and load balance. Indeed, the battery charger can charge and discharge the battery pack for various operating conditions and we can use this property for improving the reliability and flexibility. However, the major drawbacks associated to the typical on-board battery chargers for PHEVs are high volume and weight, low power, long charging time, deleterious harmonic effects on electric utility distribution systems and low flexibility and reliability. They can be integrated in different configurations to overcome these problems.

In this paper, a new battery charger structure for PHEV application using back to back (B2B) converter in a utility connected micro-grid is proposed to implement the integration of PHEV with a micro-grid and main grid. In the proposed strategy, an AC micro-grid, based on the typical household circuitry configuration, is connected to the grid via a B2B converter; and the DC link is used for battery charging. With this configuration, grid-connected AC-DC converter of battery charger will be removed.

The proposed structure is inspired from the prior works by Majumder et al. [8-10]. Indeed, [8] proposes a method for power flow control between utility and micro-grid through back-to-back converters, which facilitates desired real and reactive power flow between the utility and the micro-grid.

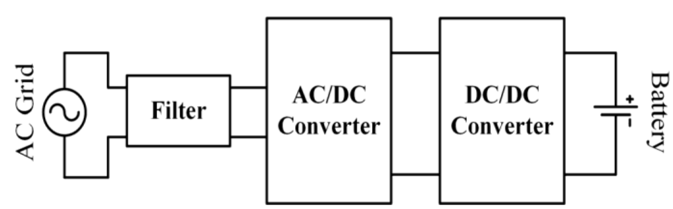


Fig. 1. A typical battery charger.

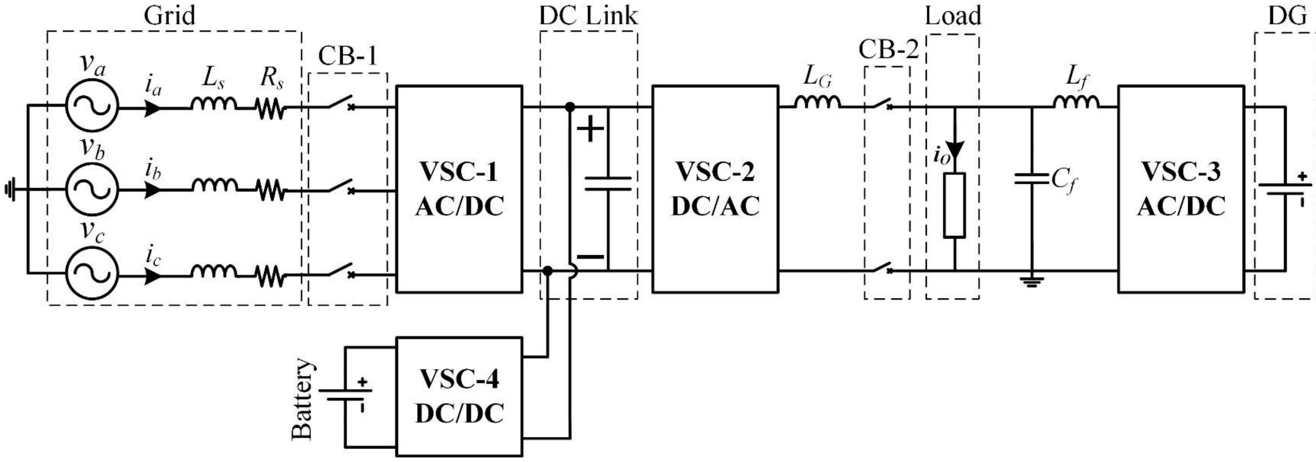


Fig. 2. Power stage of the proposed structure.

TABLE I
SYSTEM PARAMETERS

Parameter	Description	Value
C	capacitance of DC link	6 mf
C_f	LC filter capacitance	25 µF
L_f	LC filter inductance	3.7 mH
r_L	LC filter resistance	0.2 Ω
L_s	grid filter inductance	3.7 mH
V_{Load}	micro-grid load voltage (rms)	220 V
V_s	grid voltage (rms)	110 V
V_{dc}	B2B DC link voltage	400 V
V_{DG}	micro-grid DC link voltage	500 V
f_s	sampling/switching frequency	20 kHz
f	fundamental frequency	50 Hz
P	DG nominal power	1200 W

The back-to-back converters also provide the frequency isolation between the utility and the micro-grid.

The system configuration and four operational modes principles are described in this paper.

The paper is organized as follows: Section II presents the configuration and operation of the proposed system. Section III states control methods for the islanded and grid connected converter. In section IV, the performance of the proposed structure has been investigated by extensive simulations, which confirm the effectiveness of the system. Finally, Section V concludes the paper.

II. SYSTEM CONFIGURATION AND OPERATION

The power circuit of the proposed structure is shown in Fig. 2. The parameters of the circuit are listed in Table I.

Based on Fig. 2, a mathematical model, describing the dynamics of the system can be derived as

$$v_{abc} = R_s i_{abc} + L_s \frac{di_{abc}}{dt} + v_{CB-1} \quad (1)$$

$$i_{L_f} + i_{L_G} = i_O + C\frac{dv_o}{dt} \quad (2)$$

where v_{abc}, v_{CB-1} and v_o are the output voltage of the grid, the input voltage of the B2B converter and the load voltage, respectively, and i_{abc}, i_{Lf}, i_{LG}, and i_O are the grid, the filters, and load currents, respectively.

Different bidirectional AC-DC converter topologies could be used as the micro-grid and the battery charger. The specific topology chosen depends on the micro-grid and PHEV requirements such as the flexibility, cost, reliability, volume and weight [11-15]. In this paper, the converters are chosen as follows:

- VSC-1: bidirectional three-phase full-bridge AC-DC converter
- VSC-2: bidirectional single-phase full-bridge AC-DC converter
- VSC-3: unidirectional single-phase full-bridge AC-DC converter
- VSC-4: bidirectional isolated dual active full-bridge DC-DC converter

With this proposed structure, different operation modes can be created that is divided into two main categories: battery charging and discharging modes. Different categories of the battery charging and discharging modes are shown in Figs. 3 and 4, respectively. As can be seen in Fig. 3, charging mode is divided into two main categories: isolated mode that the battery only connects to the main grid (G2V) or micro-grid (M2V) and connected mode that depending on the DG power, the battery is charged from the main grid (G2V), micro-grid (M2V) or both of them (M&G2V). On the other hand,discharging mode is classified as similar as charging mode and only operation modes in connecting state is depends on the load power, not DG power. In this paper, for the full study, only the isolated cases are investigated that in this case the other modes are also included.

III. PROPOSED CONTROL METHODS FOR CONVERTERS

As mentioned before, there are three DC-AC converters in the proposed structure, which, depending on their application, are controlled. In the following, how to control the converters are examined.

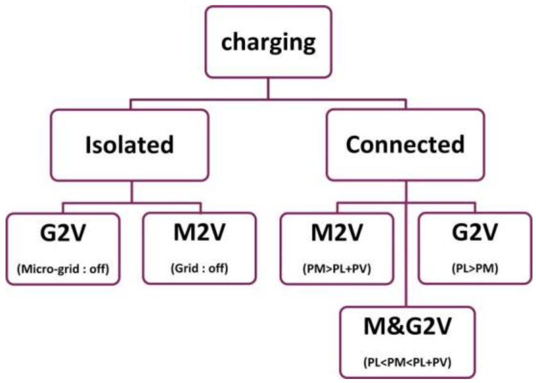


Fig. 3. Operation modes of battery charging.

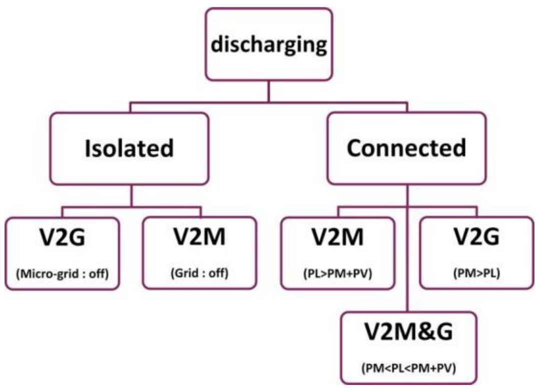


Fig. 4. Operation modes of battery discharging.

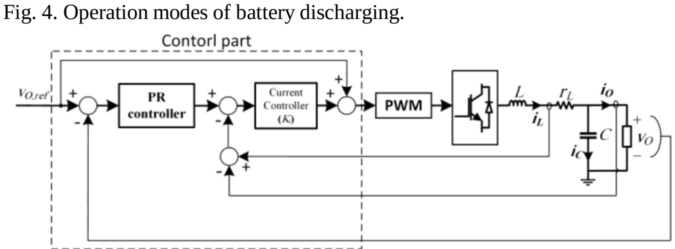


Fig. 5. Suggested control scheme for controlled voltage source inverter [15].

A. *Controlled voltage source inverter*

In this case, the inverter should be able to support the local network or critical load with the appropriate voltage and frequency from the DC input. VSC-2 and VSC-3 can should be operated in this type. Various control methods for these inverters are available in the literature. We followed offered guidelines in the [16 and 17]. Fig. 5 shows the suggested multi-loop control scheme used in this paper. The idea of multi-loop control of the output voltage of the UPS inverter with an LC filter involves an outer voltage regulation loop and an inner current loop. An outer loop with the PR controller regulates the output voltage, while the capacitor current is selected as the feedback signal in the inner control loop and provides active damping, stability over a wide range and fast dynamic for disturbances. The controller parameters are designed in the frequency domain based on the required bandwidth and stability margin [16].

B. *Controlled current source inverter*

In this case, the voltage is imposed by main grid or another inverter. Therefore, the output voltage of this type of inverter is specified and it must control its current. VSC-1, VSC-2 and VSC-3 can be operated in this type.

In this case, also, there are different control methods. An appropriate control method is presented in [19], as shown in Fig. 6 (a), which consists of the current control loop and a power control loop. The current control loop uses the PR controllers and harmonic compensators (HCs) to regulate the grid current and eliminate the low-order harmonic components [21], [22]. Furthermore, the power control loop sets deliver active and reactive power in desirable amounts.

C. *Active voltage source rectifier*

In the last converter, active voltage source rectifier is investigated, where VSC-1 and VSC-2 can be operated in this

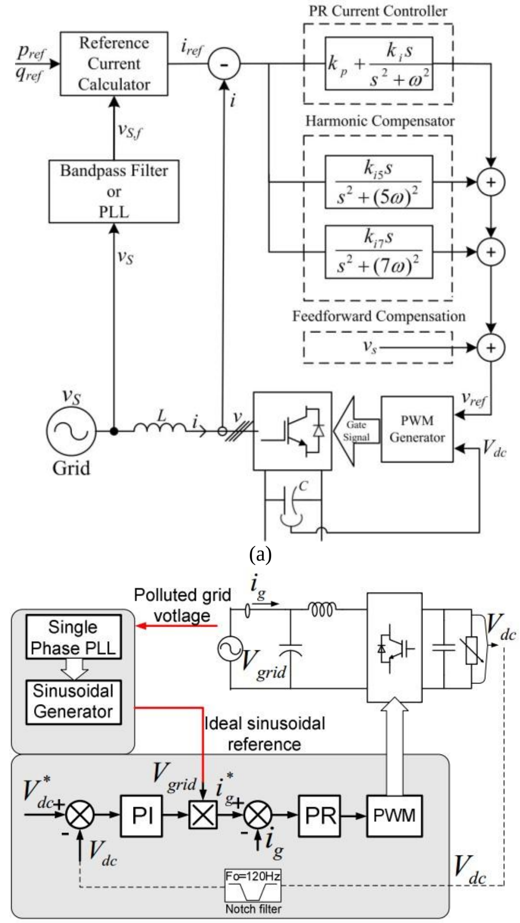


Fig. 6. Suggested control scheme for: (a) controlled current source inverter, and [17] (b) active voltage source rectifier [18].

type. Fig. 6 (b) shows the suggested control scheme for the active voltage source rectifier [18]. As shown in Fig. 6 (b), the controller uses the outer voltage loop to generate the magnitude reference for the inner current loop and the magnitude is multiplied with the phase reference supplied directly by the grid voltage. In fact, it is important to follow two aims in this controller:

1. set up DC link in a specified amount
2. Drag the current from the main grid in the same phase with the voltage of the source.

These aims are achieved in the simulations as have been investigated in the next section.

IV. SIMULATION STUDIES

To confirm the feasibility and performance of the proposed scheme, the structure of Fig. 2 has been extensively investigated using MATLAB/SIMULINK simulations. The simulation parameters are listed in Table I. As mentioned before, in this paper, only isolated cases are investigated that connected states are also included.

Fig. 7 shows the voltage and current waveforms for the battery charging operation in the grid-connected mode.

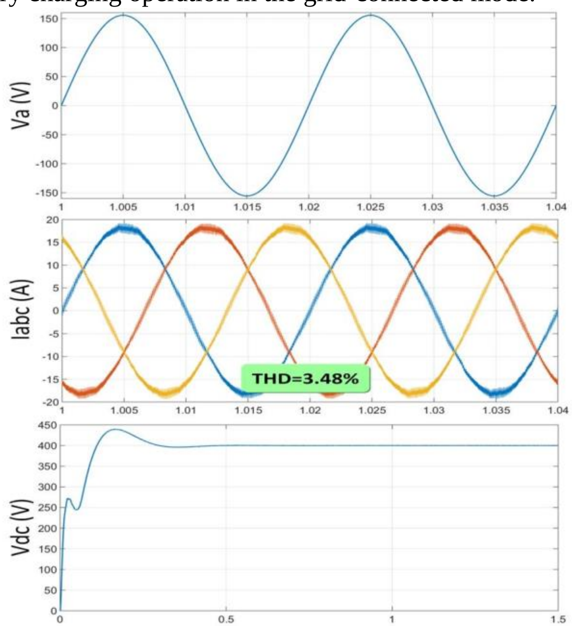


Fig. 7. Waveforms for the battery charging in grid-connected mode.

As can be seen in Fig. 7, the power factor is good (nearly one) and the DC-link voltage is reached to the desired value. Furthermore, the currents of source are sinusoidal with the total harmonic distortion (THD) of 3.48%.

Fig. 8 presents the performance of the system for the battery charging operation in the island mode. In this case, the DG is the only source and therefore, is responsible for load power and battery charging power supply. It can be seen that the load voltage and current are also sinusoidal even without the main grid, which are very good results. In fact, the load voltage remains almost unchanged during the charging mode change from grid-connected mode to island mode. Again, the DC link voltage is also set at desirable amount. This excellent performance is achieved due to the proper control of the inverter of micro-grid (VSC-3).

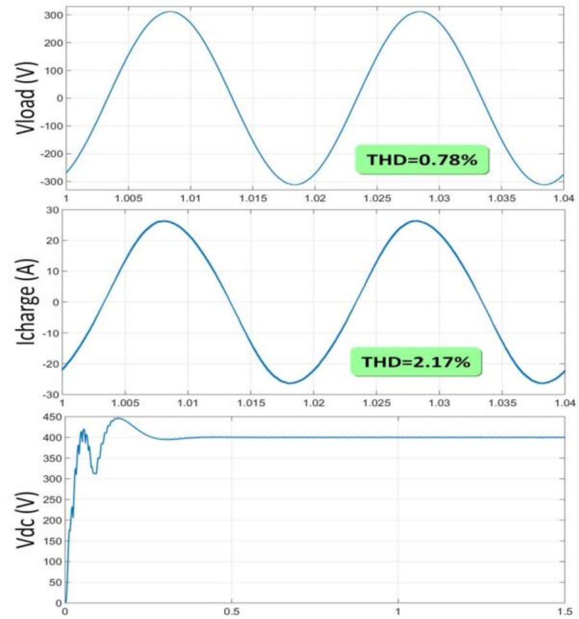
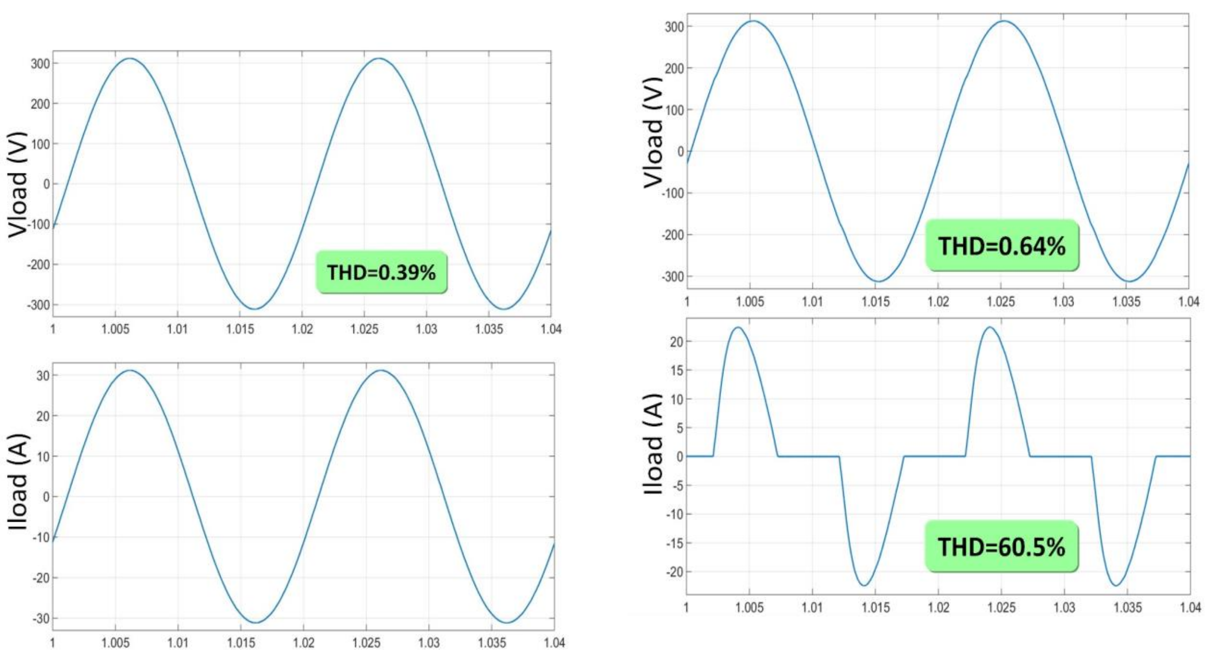


Fig. 8. Waveforms for the battery charging in islanded mode.

In another case, the battery discharging operation in the grid-connected mode is investigated and results are shown in Fig. 9. In this case, it is assumed that the battery pack delivers 2 KW to the main grid. Therefore, the actual injected power



(a)

(b)

Fig. 10. Waveforms for the battery discharging in islanded mode: (a) under the nominal linear load, and (b) under a highly nonlinear load.

tracks the reference one accurately in simulations and transient-state dies out rapidly. Furthermore, injected currents to the main grid are sinusoidal with the THD of 3.95%.

Finally, as the worst case operation, the battery discharging in island mode is investigated. In this case, it is assumed that the DG is working at the rated power (1200 W), in other words, DG works in PQ mode and battery charger (VSC-2) acts as a controlled voltage source. Therefore, the load type is important and this study is investigated in two cases. In the first case, the nominal linear load is investigated and the load waveforms are depicted in Fig. 10 (a). The load voltage is a

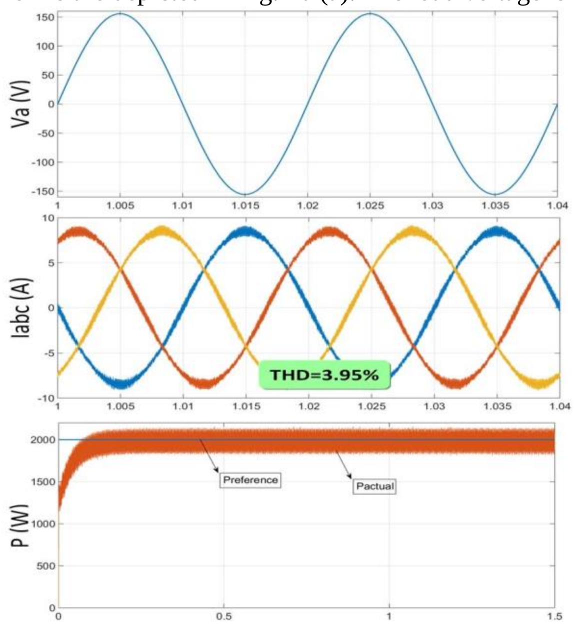


Fig. 9. Waveforms for the battery discharging in grid-connected mode.

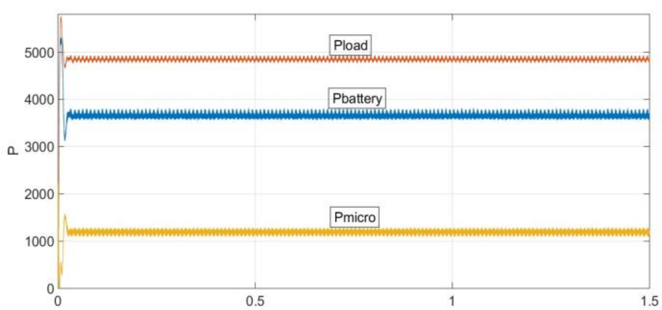


Fig. 11. The powers for the battery discharging in islanded mode under the nominal linear load.

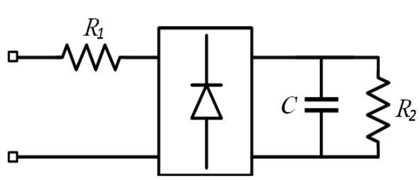


Fig. 12. Non-linear load.

perfect sinusoidal waveform with a negligible THD value (THD = 0.39%). Furthermors, the powers are shown in Fig. 11 that shows the power of the load is provided by the both battery and DG.

In the second case, the performance of the proposed scheme was evaluated under a highly nonlinear load; and the results are shown in Fig. 10 (b). The nonlinear load, shown in Fig. 12, consists of a diode rectifier bridge feeding an RC circuit through a small resistor. The values of R_1, R_2 and C are 3Ω, 30Ω and 400uF, respectively. This nonlinear load is designed according to the requirements of IEC 62040-3 standard (Annex E) [21]. One can see in Fig. 10 (b) that while the load current is highly distorted, with a THD of about 60%, the voltage waveform remains sinusoidal (THD = 0.64%). In fact, this excellent performance is achieved due to the proper control of VSC-2.

V. Conclusion

The feasibility and performance of a battery charger for PHEV application using back to back (B2B) converter in a utility connected micro-grid has been investigated in this paper. A structure has been proposed involving three parts: an AC micro-grid, in which the load is fed from the DG source, a battery charger, in which the bi-directional DC/DC converter is used, and main grid. The system infrastructure and operational principles are illustrated. The best controllers have been utilized to achieve better performances in V2M, V2G, G2V, M2V modes. In principle, the proposed scheme is very flexible and reliable, particularly for sensitive loads. The excellent performance of the proposed structure has been confirmed through extensive simulations on MATLAB/SIMULINK for various operating conditions.

References

[1] M. V. Wieringen, and R. Pop-Ilive, “Development of a Dual-Fuel Power Generation System for an Extended Range Plug-in Hybrid Electric Vehicle,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 641–648, Feb. 2010.

[2] F. Tianheng, Y. Lin, G. Qing, H. Yanqing, Y. Ting, and Y. Bin, “A Supervisory Control Strategy for Plug-In Hybrid Electric Vehicles Based on Energy Demand Prediction and Route Preview,” *IEEE Trans. Veh. Technol.*, vol. 64, no. 5, pp. 1691-1700, May. 2015.

[3] M. Yilmaz, and P. T. Krein, “Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles,” *IEEE Trans. Power Electron*, vol. 28, no. 5, pp. 2151–2169, May. 2013.

[4] Y. J. Lee, A. Khaligh, and A. Emadi, “Advanced Integrated Bidirectional AC/DC and DC/DC Converter for Plug-In Hybrid Electric Vehicles,” *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3970–3980, Oct. 2009.

[5] S. S. Williamson, A. K. Rathore, and F. Musavi, “Industrial Electronics for Electric Transportation: Current State-of-the-Art and Future Challenges,” *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 3021–3032, May. 2015.

[6] Y. Du, S. Lukic, B. Jacobson, and A. Huang, “Review of high power isolated bi-directional DC-DC converters for PHEV/EV DC charging infrastructure,” in *Proc. IEEE Energy Conversion Congr. Expo*, pp. 553–560, Sep. 2011.

[7] A. M. Bozorgi, M. Sanatkar Chayjani, R. Mohammad Nejad, and M. Monfared, “Improved grid voltage sensorless control strategy for railway power conditioners,” *IET Power Electron.*, vol. 8, pp. 2454-2461, 2015.

[8] R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, “Power Management and Power Flow Control With Back-to-Back Converters in a Utility Connected Microgrid,” *IEEE Trans. Power Electron.*, vol. 25, no. 2, pp. 821–834, May. 2010.

[9] R. Majumder, “A Hybrid Microgrid with DC Connection at Back to Back Converters,” *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 251–259, Jan. 2014.

[10] R. Majumder, “Some Aspects of Stability in Microgrids,” *IEEE Trans. Power Systems*, vol. 28, no. 3, pp. 3243–3252, Aug. 2013.

[11] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey and D. P. Kothari, "A review of single-phase improved power quality AC-DC converters," *IEEE Trans. Ind. Electron*., vol. 50, no. 5, pp. 962–981, Oct. 2003.

[12] A. M. Bozorgi, M. Monfared, and H. R. Mashhadi, "Optimum switching pattern of matrix converter space vector modulation," *in Computer and Knowledge Engineering (ICCKE)*, 2012 2nd International eConference on , 18-19 Oct. 2012 2012, pp. 89–93.

[13] R. Rahimi, E. Afshari, B. Farhangi, and S. Farhangi, "Optimal placement of additional switch in the photovoltaic single-phase grid-connected transformerless full bridge inverter for reducing common mode leakage current," *in 2015 IEEE Conference on Energy Conversion (CENCON)*, 2015, pp. 408-412.

[14] A. M. Bozorgi, M. Monfared, and H. R. Mashhadi, "Two simple overmodulation algorithms for space modulated three-phase to three-phase matrix converter," *IET Power Electron*., vol. 7, no. 7, pp. 1915–1924, Jul. 2014

[15] E. Afshari, R. Rahimi, B. Farhangi, and S. Farhangi, "Analysis and modification of the single phase transformerless FB-DCB inverter modulation for injecting reactive power," *in 2015 IEEE Conference on Energy Conversion (CENCON)*, 2015, pp. 413-418.

[16] R. Razi, and M. Monfared, "Multi-loop control of stand-alone inverters with minimum number of sensors," *IET Power Electron.*, vol. 9, no. 12, pp. 2425–2433, Oct. 2016.

[17] R. Razi, and M. Monfared, "Simple control scheme for single-phase uninterruptible power supply inverters with Kalman filter-based estimation of the output voltage," *IET Power Electron.*, vol. 8, no. 9, pp. 1817–1824, Aug. 2015.

[18] H. Jafarian, I. Mazhari, B. Parkhideh, S. Trivedi, D. Somayajula, R. Cox, "Design and implementation of distributed control architecture of an AC-stacked PV inverter" *Energy Conversion Congress and Exposition* (*ECCE*), 2015 IEEE, 2015, pp. 1130-1135.

[19] H. Gholami-Khesht, and M. Monfared, "Low computational burden grid voltage estimation for grid connected voltage source converter-based power applications," *IET Power Electron.*, vol. 8, no. 5, pp. 656–664, Apr. 2015.

[20] X. Zhou, S. Lukic, S. Bhattacharya and A. Huang, "Design and control of grid-connected converter in bi-directional battery charger for Plug-in hybrid electric vehicle application," *2009 IEEE Vehicle Power and Propulsion Conference*, Dearborn, MI, 2009, pp. 1716–1721.

[21] *Uninterruptible Power Systems (UPS)—Part 3: Method of Specifying the Performance and Test Requirements*, Second Edition 2011–03, International Standard IEC 62040-3.

[22] R. Razi, M.-S. Karbasforooshan, and M. Monfared, "Multi-loop control of UPS inverter with a plug-in odd-harmonic repetitive controller," *ISA Trans.*, vol. 67, pp. 496–506, 2017.