Grid to vehicle and vehicle to grid energy transfer using single-phase half bridge boost AC-DC converter and bidirectional DC - DC converter

Arun Kumar Verma*[1], Bhim Singh[2], D.T Shahani[3]

[1*]*Instrument Design and Development Centre, Indian Institute of Technology Delhi, New Delhi-110016, INDIA*
[2]*Department of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi-110016, INDIA*
[3]*Instrument Design and Development Centre, Indian Institute of Technology Delhi, New Delhi-110016, INDIA*
[*]*Corresponding Author: e-mail: arunvermaiitd@gmail.com, Tel +91-11-26591437,*

Abstract

A system configuration based on a single-phase unity power factor (PF) half-bridge boost converter and bidirectional DC-DC converter based energy transfer from electrical vehicle to grid(V2G) and grid to vehicle (G2V) is proposed with detailed analysis. The efficiency of this conversion system is high because there is only one series semiconductor on-state voltage drop at any instant. The analytical results are verified through simulation using switched and averaged circuit models of the system at 230V AC input and DC output. The simulation result demonstrates an improved power factor at AC mains. In the second stage, a bidirectional buck–boost DC-DC converter is used to charge and discharge the battery of the PHEV (Plug-in Hybrid Electric Vehicle). In discharging mode, it delivers energy back to the grid at 230V, 50 Hz. A battery with the charging power of 3.6 kW at 240V is used in PHEV. The buck-boost DC-DC converter is used in buck mode to charge and in a boost mode to discharge the battery.

Keywords: Plug-in Hybrid Electric Vehicle (PHEV), Half Bridge Boost AC-DC converter, DC-DC converter, Vehicle to grid (V2G), Bidirectional DC-DC converter, Power quality

1. Introduction

There are many bidirectional AC-DC PFC converters which can be used in the energy transfer from vehicle to grid (V2G) and grid to vehicle (G2V). V2G is a version of battery-to-grid power applied to vehicles. There are three different versions of the vehicle-to-grid concept (Singh et al., 2003).

- A hybrid or fuel cell vehicle, which generates power from storable fuel, uses its generator to produce power for a utility at peak electricity usage periods. Here the vehicles serve as a distributed generation system, producing power from conventional fossil fuels or hydrogen fuel cell.

- A battery-powered or plug-in hybrid vehicle uses its excess rechargeable battery capacity to provide power to the electric grid in response to peak load demands. These vehicles can then be recharged during off-peak hours at cheaper rates while helping to absorb excess night time generation. Here the vehicles serve as a distributed battery storage system to buffer power (Kempton et al., 2005; Han Sekyung et al., 2010).

- A solar vehicle uses its excess charging capacity to provide power to the electric grid when the battery is fully charged. Here the vehicle effectively becomes a small renewable energy power station (http://en.wikipedia).

The concept allows V2G vehicles to provide power to balance loads by charging at night when load demand is low and sending power back to the grid when demand is high. An electric vehicle pack has a large amount of energy stored in its battery. The energy from electrical vehicle can be transferred to the grid when there is peak demand of loads or when it is kept in parking and

simultaneously can be charged in lean period of loads. The efficient control of charging and discharging of the battery is essential to maintain good battery life, safety, and reliability.

In this paper, a configuration with single-phase half bridge bidirectional power converter is proposed for the bidirectional power transfer of a PHEV battery (http://en.wikipedia; Pandey et al., 2004,). The system can charge storage battery up to 15A current at 240V. It can also transfer energy back to the 230V, 50 Hz single-phase power at 22A rate. The proposed system is composed of two parts: a single-phase bidirectional half bridge boost AC-DC converter and a DC-DC converter. Single-phase bidirectional half bridge boost AC-DC converter is to convert AC to DC voltage (Jain et al., 2000). The buck-boost DC-DC converter is used in buck mode for charging battery and a boost mode when discharging the storage battery. The charging and discharging of the battery demonstrate the feasibility of the system.

2. System Configuration

The system configuration is shown inFig.1. A single phase bidirectional half bridge boost AC-DC converter and a bidirectional buck boost DC-DC converter are included in the system (Pandey et al., 2004; Jain et al., 2000). The structure of system shown in Fig.1 consists of an inductor connected between single phase AC and single phase bidirectional half bridge boost AC-DC converter which is necessary to boost DC output in order to charge the battery (Heydt et al., 2010). The single-phase bidirectional half bridge boost converter is designed for 4 kW and storage battery of 3.6 kWh is charged at 240V and 15A rate using bidirectional DC-DC converter. The DC-DC converter is shown in Fig.2. In charging mode, the DC bus voltage must be higher than the battery voltage, in charging mode the circuit becomes buck converter circuit (Mohan et al., 1995). Through controlling the PWM duty ratio in buck mode, the charging current is controlled. In discharge mode this circuit becomes a boost converter circuit.
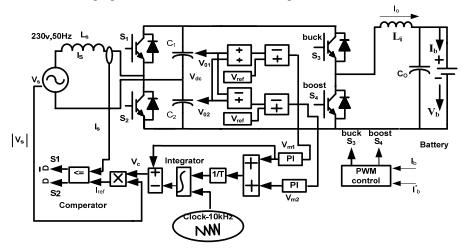

Fig.1 Proposed Configuration for V2G and G2V Energy Transfer

3. Design of the System

The design of the various components of proposed configuration for energy transfer from grid to vehicle and vehicle to grid consists of a single phase half bridge boost AC-DC converter, a bidirectional DC-DC boost converter, and a battery energy storage system. The detailed design of each part is given in the following sections.

3.1 Design of Single-Phase Half Bridge Boost AC-DC Converter

In the half-bridge boost AC-DC converter topology shown in Fig. 1, the voltage drop of semiconductor devices at any instant of time is only one device. In addition to the above advantage, the half-bridge boost converter can regenerate the output power, while the single-switch boost rectifier cannot feed energy back to the source (Wall et al 1997). The half-bridge boost rectifier may be used in application requiring high DC bus voltage such as UPS systems, a line conditioner and a single-phase to three-phase power conversion. Let us consider that the input source voltage V_s is given as,

$$V_s = V_{sm} \sin wt \tag{1}$$

where V_{sm} is the maximum value of the source voltage the value of V_{sm} is 325V for $V_s = 230$V rms and $\omega = 2\pi f$. The input current is given as (Ramesh et al., 1998),

$$i_S = \frac{V_S}{R_e} = I_{sm} \sin wt \tag{2}$$

where R_e = emulated resistance. The value of V_s is 230V. The normalized input voltage M_s is given as,

$$M_S = \frac{V_{sm}}{V_{dc}} = M_g \sin wt \tag{3}$$

where the value of V_s is 325V and the value of V_{dc} is 800 V. The calculated value of M_s from eq. (3) is 0.40625. The value of emulated resistance (R_e) is given as,

$$R_e = \frac{V_{sm}^2}{2P_0} \tag{4}$$

where V_{sm} is 325V and P_o is output power. The value of P_o is 4kW. The calculated value of R_e is 13.20Ω
The normalized input voltage M_s is as shown in eq. (3), where $M_s = V_{sm}/V_{dc}$. The input-output power balance equation is shown in eq. (4), where the internal losses are neglected. Eq. (1) to eq. (4) are used in the analysis, design and modeling of the above converter systems. The value of the interfacing inductor is given as (Rajesh et al., 2007),

$$L_s = \frac{M_s V_{dc}^2}{8P_0 f_{sw}(\frac{\Delta I_{s\max}}{I_{s\max}})} \tag{5}$$

where ($\Delta I_{smax}/I_{smax}$) is the input current ripple and it is considered to be 10%. f_{sw} is switching frequency and its value is 10 kHz. The calculated value of the interfacing inductor from eq. (5) is 6.5mH.
The zero crossing of the capacitor current is given as (Rajesh et al., 2007),

$$\theta_1 = \sin^{-1}[\frac{\sqrt{1 + 8M_s^2} - 1}{4M_s}] \tag{6}$$

The calculated value of the θ_1 from eq. (6) is 18.7⁰. The output capacitor of half bridge boost AC-DC converter is given as (Rajesh et al., 2007),

$$C_1 = C_2 = \frac{P_0}{W * V_{dc}^2[\frac{\Delta v_{0(\max)}}{V_{dc}}]}[\frac{2}{M_s}\cos\theta_1 + 2\sin\theta_1] \tag{7}$$

where $\omega = 2\pi f$ and $\frac{\Delta v_{0(\max)}}{V_{dc}}$ is % ripple voltage and the value of ripple voltage is taken as 10%. The calculated value of the output capacitor from eq. (7) is 3.06mF. The input power factor of the configuration is given as (Rajesh et al., 2007),

$$\cos\theta = \cos[\tan^{-1}(\frac{X_L}{R_e})] \tag{8}$$

The calculated value of the power factor from eq. (8) is 0.9818 (Ramesh et al., 1998; Rajesh et al., 2007). Detailed model parameters are given in Appendix.

3.2 *Design of Bidirectional Buck Boost DC-DC Converter*

The bidirectional buck-boost DC-DC converter is shown in Fig.2. The solid state switch S_3 is used for buck mode of operation while the switch S_4 is used for the boost conversion mode. The buck mode is used for charging and boost mode is used for discharging the battery. The relationship between switching frequency f_{sw}, inductance L_i, in buck–boost mode is given as (Saber et al., 2010),

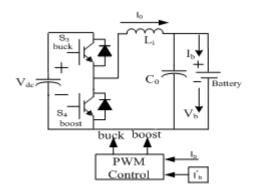$$f_{sw} = \frac{1}{2 * P * L_i}\left(\frac{1}{\frac{1}{V_{dc}} + \frac{1}{V_b}}\right) \tag{9}$$

where P is conversion power, V_{dc} ($V_{o1}+V_{o2}$) is input voltage and V_b is output voltage and f_{sw} is the switching frequency and its value is 50 kHz. The value of P is 4 kW, V_{dc} input voltage 800V and V_b is output voltage is 240 V. From eq. (9), the value of L_i is 3.23 mH (Kisacikoglu et al., 2010). Detailed design parameters are given in Appendix

3.3 Design of Storage Battery

The charging and discharging of battery play an important role in PHEV. A lead-acid model battery is implemented in MATLAB/simulink using a model given in (Massimo et at al., 2000). Fig. 3 shows a Thevenin's equivalent of the storage battery as an energy unit. Its storage energy is represented in kWh which is stored in an equivalent capacitor (C_b) expressed as,

$$C_b = (kWh*3600*1000)/\{0.5(V_{ocmax}^2 - V_{ocmin}^2)\} \tag{10}$$

where V_{ocmax} is the voltage at the terminal of the battery when it is fully charged and V_{ocmin} is the voltage at the terminal of the battery when it is fully discharged. In this equivalent model of the battery (Massimo et at al., 2000), R_s is the equivalent series resistance of the battery, the value of R_s is taken 0.01Ω. The parallel circuit of R_b and C_b represents the self discharging of the battery. The value of R_b for this battery is taken as 10kΩ. Here the battery is designed, having capacity of 3.6 kW for 15 Hrs, and with the variation in the voltage of order of 212 V to 272V. The calculated value of C_b for this battery is from eq. (10) is calculated as 3616.92 F (Massimo et at al., 2000).
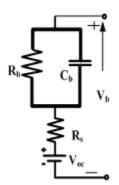

Fig.2 Bidirectional buck-boost DC-DC converter   Fig.3 Thevenin's equivalent circuit of storage battery

4. Control Algorithm

The control algorithm for different blocks of proposed system is given in this section. The control algorithm plays an important role in the operation of such system and it is explained as follows.

4.1 Control of Half Bridge Boost AC-DC Converter

A half-bridge converter system is shown in Fig.1. In each switching cycle T_s, the converter switches S_1 and S_2 are turned on and turned off by complementary gating pulses. S_2 is turned on for duration of DT_s and S_1 for $(1-D) T_s$, where D is the duty ratio. With S_2 on and S_1 off, the voltage applied across inductor L is $(V_S + V_{o2})$. Again, with S_1 on and S_2 off, the same is $(V_S - V_{o1})$. The switching frequency ($f_{sw} = 1/T_s$) is considered to be high. The duty ratio D is given by the volt-second balance across the inductor is given as

$$V_s = V_{01} - D(V_{01} + V_{02}) \tag{11}$$

Since a half-bridge converter has a split DC bus, both the output voltages V_{o1} and V_{o2} must be controlled. These two voltages must also be equal in the steady state condition. Here a PI (Proportional integral) voltage controller is used each for controlling V_{o1} and V_{o2} as shown in Fig. 1. The outputs of the two controllers P_{i1} and P_{i2} are V_{m1} and V_{m2}, respectively. The two outputs V_{m1} and V_{m2} are used to control the emulated resistance, R_e, of the whole converter. The output of PI controller 1 is given as,

$$V_{m1} = V_{ref}^* - (V_{o1} + V_{02})K_1 \tag{12}$$

where V_{ref} is considered as 800V.
The output of PI controller 2 is given as,

$$V_{m2} = V_{ref}^* - (V_{o1} - V_{02})K_2 \tag{13}$$

Consider V_c is the required carrier wave when $V_{o1} = V_{o2}$, and $V_{m1} = V_{m2}$. The corresponding switching instants for S_1 and S_2 are determined by the intersection of I_{ref} with I_s. It should be noted that the positive and the negative peaks of V_c are (V_{m1}) and $(-V_{m2})$ respectively, as per eqs. (11), (12). Now if V_{o1} tends to become less than the desired reference level, while V_{o2} is equal to the reference, the voltage controller, controls V_{o1} and ensures $(V_{m1} =) > V_{m2}$. The modified carrier wave is used to generate the modified gating pulses for S_2 and S_1 respectively. This results in transfer of excess energy, stored in C_2, to C_1 to balance both V_{o1} and V_{o2}. Similar explanation may be given for other mode of operation (Medina et al., 2010, Rajesh et al., 2007).

4.2 Control of Bidirectional DC-DC Converter

In order to control the charging and discharging of the battery using a bidirectional buck-boost converter, a technique based on PWM control is used here. A proportional integral (PI) controller is used to control the output DC current. The PI voltage controller closely monitor the reference DC link current and generate a control signal (V_{cs}) to reduce the current error $I_{es}(k)$ which is generated from the reference DC link current $I^*_b(k)$ and a sensed DC link current $I_b(k)$ at k_{th} instant of time as,

$$I_{es}(k)=I^*_b(k)-I_b(k) \tag{16}$$

The output of the PI controller $V_s(k)$ at k_{th} instant is given as,

$$V_S(k)=V_S(k-1)+K_{pv}\{I_{eS}(k)-I_{eS}(k-1)\}+K_{iv}I_{eS}(k) \tag{17}$$

where K_{pv} and K_{iv} are the proportional and integral gains of the voltage controller. This technique is applicable for buck-mode as well as boost mode. The output of the controller $V_S(k)$ at k_{th} instant is compared with fixed frequency (f_{sw}) saw-tooth carrier waveform to get the control signals for the solid state devices of the bidirectional buck-boost converter (Kisacikoglu et al., 2010). Detailed design parameters are given in Appendix.

5. Matlab based Modeling

The MATLAB/SIMULINK model of the proposed topology for energy transfer from the vehicle to grid and grid to vehicle is shown in Fig.4. It consists of a model of single-phase bidirectional half bridge AC-DC converter. This single-phase half bridge bidirectional AC-DC converter is designed for a power of a 4kW.The bidirectional DC-DC buck-boost converter is used for charging and discharging of the battery of PHEV. The detailed design parameters of bidirectional buck-boost converter are given in Appendix. An energy storage system is designed for the capacity of 3.6 kW for 15 Hours within the voltage variation in the voltage of 212 V to 272V. Detailed designed parameters of storage battery are given in Appendix. Simulation is carried out in MATLAB version of 7.8 the sim power system toolbox using ode (26tb/stiff/TR-BDF-2) solver in discrete mode at 1e-6 step size.
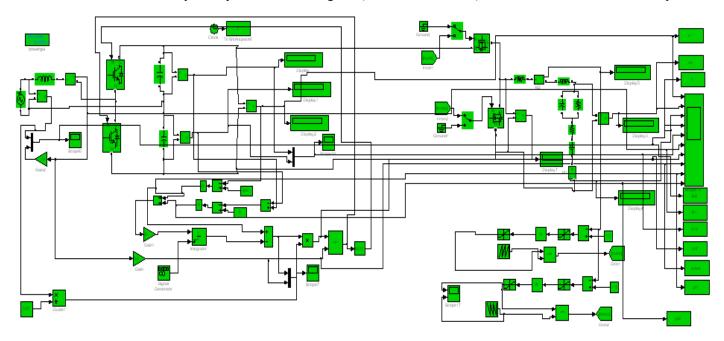

Fig.4 MATLAB/SIMULINK model for energy transfer from vehicle to grid and grid to vehicle

6. Result and Discussion

Simulated results are presented for plug-in modes in Figs. 5-8. The current delivered from the grid while charging is shown to be sinusoidal and in phase with the grid voltage. This eliminates current harmonics and maintains a unity power factor. When delivering power to the grid while discharging, the injected current is in the phase opposition of the grid voltage, which can be seen from 180° phase difference and it has maintained unity power factor operation. Although some brief voltage disturbances occur during abrupt load changes, the converter maintains constant DC link voltage, while supplying or absorbing the required current. The rise and fall in the battery voltage while charging and discharging are shown in these figures corresponding to the maximum and minimum open circuit battery voltages. The voltage profile is demonstrated in Figs.5-8. Fig.5 shows the complete profile of charging and discharging of electrical vehicle. From 0 to 3s, the battery of electrical vehicle is in charging mode at 3s the battery is switched in to discharging mode. There are some fluctuations in the DC link voltage at this point which are

minimized with effective control. In Fig.6 the charging mode of battery is switched to discharging mode the switching state of conversion is shown in which the battery current has become negative and the grid current is out of phase with grid voltage. There is change in the mode of operation i.e. from buck mode to boost mode. In Fig.7 at 2s to 2.2 s, charging mode of operation is shown i.e. boost mode. The voltage across capacitors C_1 and C_2 are V_{o1} and V_{o2} which are shown in this Fig.6. The battery is charged at 15A rate.
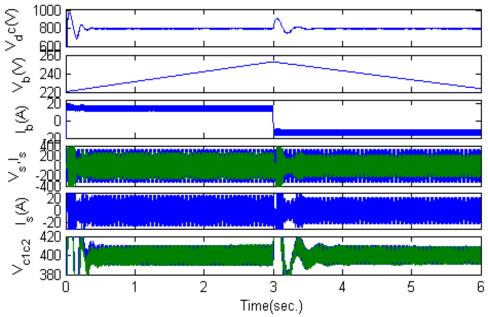

Fig.5 Charging and discharging of PHEV battery (Full profile)

The value of the source current is 25A. Fig.8 shows the discharging mode of operation from 5s to 5.2s and at the same point of time the direction of current is in 180^0 phase opposition. This shows the reversal of current and flow of power in reverse direction. The value of the current fed back to grid is 22.5A. In these figures, while showing V_s, I_s in same figure, I_s, grid current is amplified by factor of 10 in order to observe it in comfortably to the given axes. The harmonics spectra for the charging current from grid and discharging current to grid are shown in Fig.9 and Fig.10 respectively. The Total Harmonic distortion (THD) of the charging and discharging current is well within the limit of IEEE-519 standard. The different power quality parameters like current and voltage THD are given in Table-1.
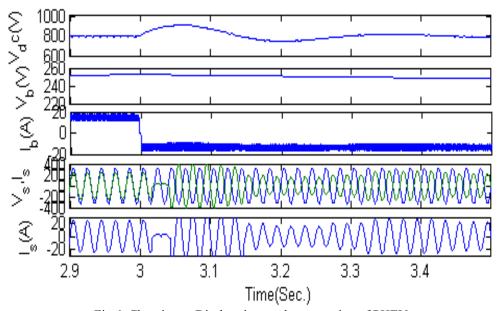

Fig.6. Charging to Discharging mode conversion of PHEV

Table 1 shows the parameters like total harmonic distortion (THD) of grid voltage as well as the grid current in charging and discharging mode. The THD of AC mains current are 4.46 and 4.53 respectively which are well within the acceptable limit of IEEE 519. The power factor of the grid current in charging and discharging mode is near to unity and values are 0.9818 and 0.982 respectively.
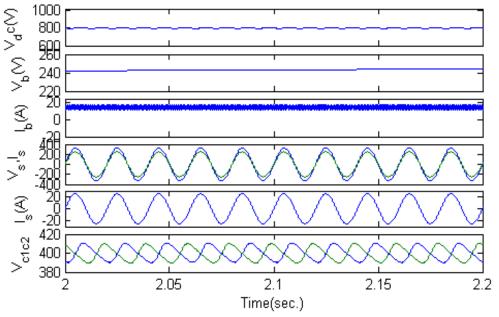
Fig.7. Charging of PHEV battery demonstrating unity power factor operatio

7. Conclusions

The proposed system has been found suitable for charging and discharging the battery of PHEV. A high efficiency of around 96% is achieved under low-input voltage condition due to a reduced number of semiconductor on-state drops and the use of reduced switches. The proposed converter has delivered the AC current to/and from the grid at unity power factor and at very low current harmonics which ultimately prolongs the life of the converter and minimizes the possibility of distorting the grid voltage.
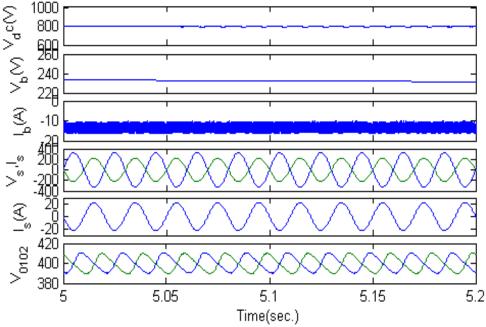
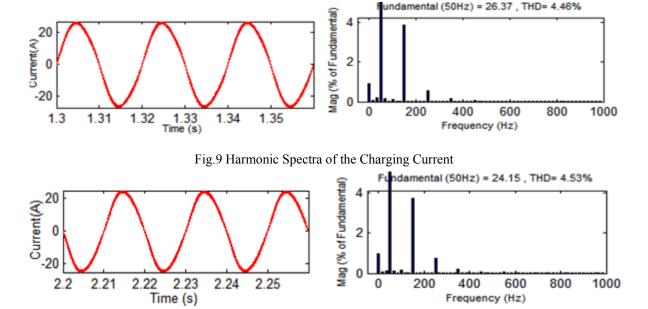Fig.8 Discharging of PHEV battery (in large view)

Fig.9 Harmonic Spectra of the Charging Current

Fig.10 Harmonic Spectra of the Discharging Current

Table-1: Power Quality Parameter during charging and discharging mode.

Serial no. mode	Charging mode	Discharging mode
Current THD % of I	4.46	4.53
Voltage THD % of V	0.81	1.32
Power Factor (P.F)	0.9818	0.982

8. Appendixes

Parameters for Single-Phase Half bridge boost AC-DC Converter
K_{i1}=0.25, k_{p1}=0.1, L_s = 2.3mH, K_{i2}=0.009, k_{p2}=0.6, 4000W, 230V rms, f_s = 20 kHz, L= 6.5Mh,C_1= C_2= 3.06mH.
Parameters for Bidirectional DC-DC Buck Boost Converter
Buck mode, K_{i1}=1, k_{p1}=0.001 for Boost mode, K_{i2}=0.5, k_{p2}=0.01, F_s = 50 kHz, L_0 = 3.23 mH.
Parameters for Storage Battery
R_b=10 kΩ, R_s=0.01Ω, V_{oc}=240V.

References

Rajesh Ghosh May 2007, "Modeling, Analysis and Control of Single-Phase and Three-Phase PWM Rectifiers. A Ph.D Thesis, Indian Institute of Science, Bangalore.

Han Sekyung, Han and Soohee K.Sezaki., 2010. Development of an Optimal Vehicle-to-Grid Aggregator for Frequency Regulation IEEE *Transactions on Smart Grid,* vol.1, no.1, pp.65-72.

Heydt G.T., 2010. The Next Generation of Power Distribution Systems. *IEEE Transactions on Smart Grid,* vol.1, no.3, pp.225-235.

http://en.wikipedia.org/wiki/Vehicle-to-grid

Jain M., Daniele M., and Jain P.K., Jul 2000. A bidirectional DC-DC converter topology for low power application. *IEEE Transactions on Power Electronics.,* vol.15, no.4, pp.595-606.

Kempton. W. and Tomic J., June, 2005.Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. *J. Power Sources*, vol. 144, no. 1, pp. 280–294.

Kisacikoglu M.C., Ozpineci B., and Tolbert L.M. Examination of a PHEV bidirectional charger system for V2G reactive power compensation. in *Proc. of Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2010*, 21-25 Feb.2010, pp.458-465.

Massimo Ceraola.Nov. 2000. New Dynamic models of lead-acid batteries. *IEEE Trans. on Power Systems,* vol.15, no.4, pp. 1184-1190.

Medina J., Muller N. and Roytelman I. 2010. Demand Response and Distribution Grid Operations: Opportunities and Challenges. *IEEE Transactions on Smart Grid,* vol.1, no.2, pp.193-198.

Mohan N., Undeland T. and Robbins W. 1995. *Power Electronics: Converters, Applications and Design,* second edition (John Wiley & Sons, New York.

Pandey A., Singh B., and Kothari D. P. Sept. 2004. Comparative Evaluation of Single-phase Unity Power Factor AC-DC Boost Converter Topologies Journal of IE (I), Vol.85, pp.102-109.

Ramesh Srinivasan and Ramesh Oruganti May 1998. A Unity Power Factor Converter Using Half- Bridge Boost Topology. *IEEE Transactions on Power Electronics*, vol. 13, no. 3.pp. 78-83.

Saber A.Y., Venayagamoorthy G.K. 2010.Efficient Utilization of Renewable Energy Sources by Gridable Vehicles in Cyber-Physical Energy Systems. *IEEE Systems Journal,* vol.4, no.3, pp.285-294.

Singh B., Singh B. N., Chandra A., Kamal Al Haddad, Pandey A., and Kothari D. P., 2003. A review of single-phase improved power quality ac–dc converters. *IEEE Trans. Industrial Electronics*, vol. 50, no. 5, pp. 962-981

Wall.S and Jackson R. Oct.1997. Fast controller design for single-phase power-factor correction systems*. IEEE Trans. Ind. Electron.*, Vol.44, no.5, pp**.** 654–660.

Biographical notes

Arun Kumar Verma received B.E. DCRUST Mutharal (Sonepat) Harayana India in 2003 and M.Tech from Indian Institute of Technology Delhi (India) in 2010. Currently he is perusing Ph.D from Indian Institute of Technology Delhi. His research interests include Power Electronics, Electrical machines and Renewable Energy. He is a student member of IEEE.

Bhim Singh received his B.E. in Electrical Engineering from the University of Roorkee, Roorkee, India, in 1977 and his M.Tech. and Ph.D. from the Indian Institute of Technology (IIT) Delhi, New Delhi, India, in 1979 and 1983, respectively. In 1983, he joined Department of Electrical Engineering, University of Roorkee, as a Lecturer, and in 1988 he became a Reader. In December 1990, he joined Department of Electrical Engineering, IIT Delhi, as an Assistant Professor. He became an Associate Professor in 1994 and a Professor in 1997. He has guided 38 Ph.D. dissertations, 120 M.E./M.Tech./M.S.(R) theses, and 60 BE/B.Tech. Projects. His areas of interest include power electronics, electrical machines and drives, renewable energy systems, active filters, FACTS, HVDC and power quality. Dr. Singh is a Fellow of the Indian National Academy of Engineering (INAE), the National Science Academy (NSc), the Institute of Electrical and Electronics Engineers (IEEE), the Institute of Engineering and Technology (IET), the Institution of Engineers (India) (IE(I)), and the Institution of Electronics and Telecommunication Engineers (IETE). He is also a life member of the Indian Society for Technical Education (ISTE), the System Society of India (SSI), and the National Institution of Quality and Reliability (NIQR). He received the Khosla Research Prize of the University of Roorkee in the year 1991. He was the recipient of J.C. Bose and Bimal K. Bose Awards of the Institution of Telecommunication Engineers (IETE) for his contributions in the field of power electronics in the year 2000. He was also a recipient of the Maharashtra State National Award of the Indian Society of Technical Education (ISTE) in recognition of his outstanding research work in the area of Power Quality in the year 2006. He received the PES Delhi Chapter Outstanding Engineer Award for the year 2006. He was the General Chair of the IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES'2006) and (PEDES'2010) held in New Delhi.

D.T Shahani received his Ph.D from Indian Institute of Technology Delhi. Currently he is professor with Instrument Design and Development Centre, Indian Institute of Technology Delhi. His area of Interest is Electronic Instrumentation, Electromagnetic, and Antennas.