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Control of Energy Storage Interface with a Bidirectional Converter for Photovoltaic Systems

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Abstract

Efficient energy storage is one of the greatest concerns for renewable power generation. This paper focuses on the control of a battery management system (BMS) for photovoltaic (PV) applications with a high efficiency bidirectional converter. The proposed BMS control strategy utilizes the dc bus power and battery state of charge (SOC) for the charging and discharging of the battery with a bidirectional converter. The bidirectional converter includes fewer components and switches, has less switching losses with zero voltage switching, and has high gain buck-boost operations. A new control algorithm of charging-discharging control for the battery storage system is proposed. The complete PV system with a boost dc to dc converter controller to regulate the dc link voltage, bidirectional converter based battery charge controller, and an inverter with its associated vector mode controller is implemented in the Simulink/Simpower environment. The simulation results are presented and discussed to verify the validity of the proposed control algorithm.

Keywords

Control, Energy, Storage, Interface, Bidirectional, Converter, for, Photovoltaic, Systems

Disciplines

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***Abstract* - Efficient energy storage is one of the greatest concerns for renewable power generation. This paper focuses on the control of a battery management system (BMS) for photovoltaic (PV) applications with a high efficiency bidirectional converter. The proposed BMS control strategy utilizes the dc bus power and battery state of charge (SOC) for the charging and discharging of the battery with a bidirectional converter. The bidirectional converter includes fewer components and switches, has less switching losses with zero voltage switching, and has high gain buck-boost operations. A new control algorithm of charging-discharging control for the battery storage system is proposed. The complete PV system with a boost dc to dc converter controller to regulate the dc link voltage, bidirectional converter based battery charge controller, and an inverter with its associated vector mode controller is implemented in the Simulink/Simpower environment. The simulation results are presented and discussed to verify the validity of the proposed control algorithm.**

I. INTRODUCTION

The integration of photovoltaic (PV) power systems and energy storage schemes is one of the most significant issues in renewable power generation technology. The rising number of PV installations due to increasingly attractive economies, substantial environmental advantages and supportive energy policies require enhanced strategies for their operation in order to improve the power supply stability and reliability [1-2].

Energy storage system for the PV power generation is addressed in the literature. Some [3-10] concentrates on the system configurations as well as control strategies whereas some others [11-15] focus solely on the converter topologies or on the control techniques.

In the conventional PV system architecture, the PV power is transferred to the load through a unidirectional and a bidirectional converter where a considerable amount of power loss occurs in each conversion stage. Hence, the system efficiency deteriorates with the increasing number of power conversions. These disadvantages arise from the fact that both of the converters in the conventional system process the PV array output power [9].

In some previous applications [5-8, 12], the battery-bank is directly connected to a dc bus without a bidirectional converter. This configuration requires more battery stacks and reduces the system efficiency. Also, the battery life is degraded without proper control of charging and discharging of the battery. Though series strings of storage batteries provide high voltage, a slight mismatch or temperature difference can cause charge imbalance if the series string is charged as a unit [10]. Such high voltage batteries are expensive and produce more arcing on the switches than the low voltage batteries. Another problem with higher voltage batteries is the possibility of one cell failing. A faulty cell would produce lower voltage, however, in an extreme case, one open cell could break the current flow [16].

In the customary bidirectional converters, more switches and transformer-based schemes increases production costs and reduces conversion efficiency [11]. Moreover, the conventional PV energy storage systems use time based energy scheduling to operate the operation mode control of the battery charger based on the time setting [9]. In these control methods, battery charging and discharging may be disrupted due to overcast weather.

This paper addresses the above limitations of the existing works and designs a PV storage system with a well-organized architecture having a high efficiency bidirectional converter and a novel control algorithm. The objective of this paper is to propose a control algorithm of the battery charger for photovoltaic applications, where the control strategy lies in the dc bus power and battery state of charge (SOC) estimation. An efficient bidirectional converter is included in this PV battery management system (BMS) to improve the overall efficiency.

II. SYSTEM CONFIGURATION

A. *Power Management and Controller Implementation*

The purposes of the power management (Fig. 1) and control system architecture (Fig. 2) are to satisfy the load power demand and to maintain the state of charge of the battery bank within a specified limit to prevent blackouts and to extend the battery life. As there are two energy sources in the system, it requires managing the sources to ensure reliability, optimal operation and cost effectiveness. In this case, the PV generation profile, the residential load profile and the battery storage profile needs to be considered. Table I shows the specifications of the system. The concept of energy transfer is achieved by using a novel control algorithm incorporated with the bus power and battery SOC. A good regulation capability is achieved with the proposed control method.

The control strategy used here consists of three parts. First part is the converter controller for voltage regulation, the second part is the battery charging and discharging controller using the bidirectional converter, and the third part is the inverter controller for obtaining ripple-free power.

B. PV Module

A PV module, which converts light into electricity, can be modeled as a single diode model, as shown in Fig. 3. The relationship among different currents and voltages of the equivalent circuit model of PV module is given by,

$$I_{LG} - I_D - \frac{V_D}{R_{sh}} - I_{pv} = 0 \qquad (1)$$

$$V_{pv} - V_D + I_{pv} R_s = 0 \qquad (2)$$

where, I_{LG} (A) is the light generated current; I_D is the diode current; V_D is the diode voltage; R_{sh} (Ω) is the shunt resistance; R_s (Ω) is the series resistance; I_{pv} (A) and V_{pv} (V) are PV module output current and output voltage, respectively.

The operating equation of the PV module can be easily derived as [17],

$$I_{pv} = I_{LG} - I_{sat}\left(e^{\frac{q}{nkT}(V_{pv} + I_{pv} R_s)} - 1 \right) - \frac{V_{pv} + I_{pv} R_s}{R_{sh}} \qquad (3)$$

where, I_{sat} (A) is the PV module saturation current; T (K) is the PV module temperature and k is Boltzmann constant.

The electrical output characteristics of the PV module are shown in Fig. 4. This figure is exposed to a specified amount of irradiance (1000 Wm^{-2}) at a constant ambient temperature (25^0 C). The PV panel is operated usually at or near maximum power point (MPP) for optimum performance of the system.

A Simulink model of the PV module, shown in figure 5, is used as the PV source. This model takes solar irradiance and PV module current as input and gives PV module voltage and power as the output. Different parameters of the circuit, such as short circuit current, open circuit voltage, current and voltage at MPP can also be set in the model [18].

C. DC/DC Converter Control

The dc link collects the energy generated by the PV source and delivers it to the load and, if necessary, to the battery banks. A classical boost converter is used as the dc-dc conversion interface. The utility ac voltage is usually 230V and thus requires a dc voltage of about 380V at the output of the dc-dc converter. Since the voltage of PV module is usually below this level, the system raises the voltage level using the boost converter. The hysteresis current control (HCC) method, as shown in Fig. 6, is used as the converter controller to stabilize the voltage level of the dc bus. This method operates at a variable frequency. The hysteretic controller provides the gating signal for switch on-off as necessary to maintain a waveform within a given limit. The switch is either in 'on' or 'off' position according to the response of zero current detector (ZCD). The ZCD senses the inductor current (i_L).

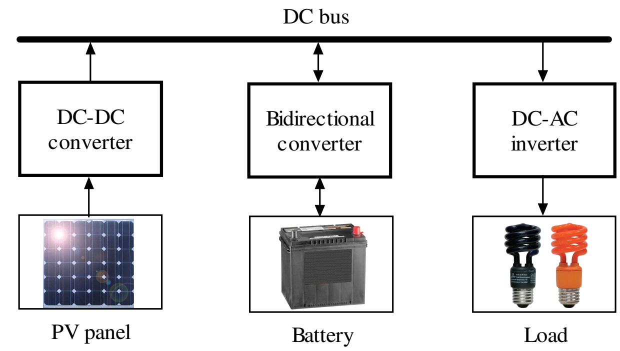

Figure 1. Power circuit of the PV BMS.

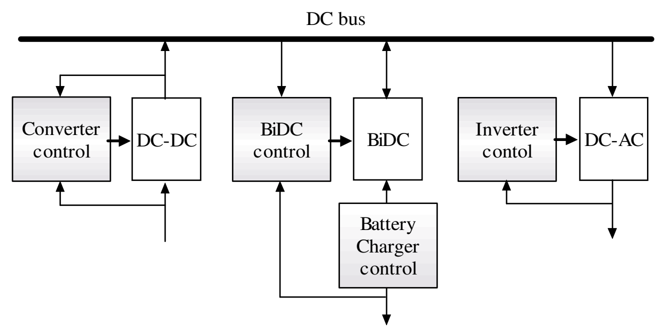

Figure 2. Control circuit of the PV BMS.

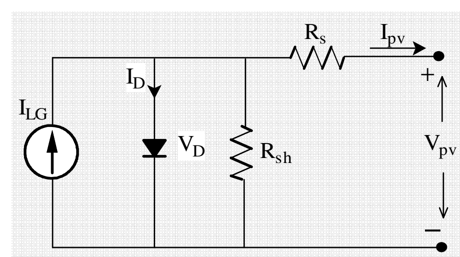

Figure 3. Equivalent circuit of PV module.

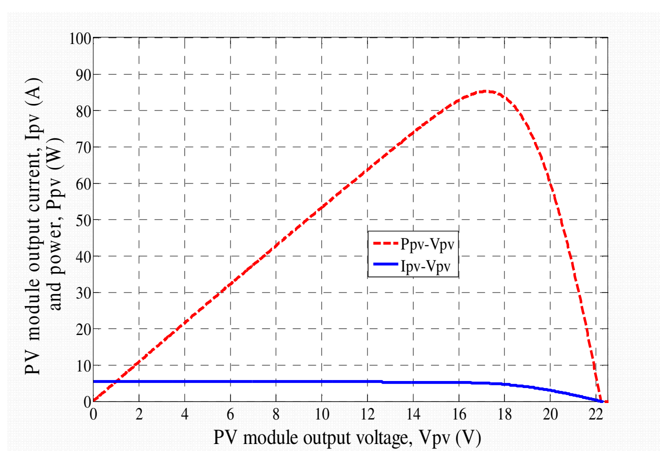

Figure 4. Current-voltage and power-voltage characteristics of a PV module at a constant temperature and specified irradiance.

D. Bidirectional Converter Control

The efficiency, reliability and dynamic performance of the system relies on the operation of the bidirectional converter under different modes of operation, so that individual parts of the system can operate properly. A buck-boost type high performance bidirectional converter, as shown in Fig. 7, is used to charge and discharge the battery. This bidirectional converter is having the following properties which enhance its performance,

- power flow with large voltage diversity
- high step-up and step-down ratio
- soft switching and zero voltage switching
- reduced switching losses due to fewer switches
- less conduction losses
- synchronous rectification
- no transformers
- no magnetizing current saturation
- less weight and volume

The voltage gain of the bidirectional converter in the buck state can be expressed as [11],

$$G_{V1} = \frac{V_L}{V_H} = \frac{d_3(1-d_3)}{N(1-d_3)+1} \tag{4}$$

and the voltage gain of the bidirectional converter in the boost state can be represented as,

$$G_{V2} = \frac{V_H}{V_L} = \frac{2+N}{1-d_1} \tag{5}$$

where, V_L and V_H are the battery terminal voltage and dc link voltage respectively. d_3 and d_1 are the duty cycle of switch S_3 and S_1 respectively. N is the turn ratios of the coupled inductor L_P and L_S, as shown in Fig. 7.

The proposed battery charger algorithm (Fig. 8) uses the data obtained from the dc bus power and the battery state of charge. Depending on the system operating conditions, the operation mode controller generates the mode selection control signal. To balance the power flow in the system and to achieve the power conditioning compatibility, this controller operates readily. The battery SOC would be adjusted to match the power demand of the load. For this reason, the inner power loop goes with outer battery SOC to adjust the charging algorithm.

If the battery SOC is below 90% and the dc link has sufficient power from the PV module to charge the battery, then the bidirectional converter acts as a buck converter and charges the battery. On the other hand, if the battery SOC is above 40% and the load needs support from the battery, then the bidirectional converter acts as a boost converter and delivers power from the battery to the load. Whenever the battery is overcharged or has no sufficient charge to deliver, then it automatically goes to the halt mode.

Control of the bidirectional converter is the key factor of the power management. To manage the energy exchanges between the dc link, the PV module and the storage device, three operating modes are employed which are charging, discharging and halt mode.

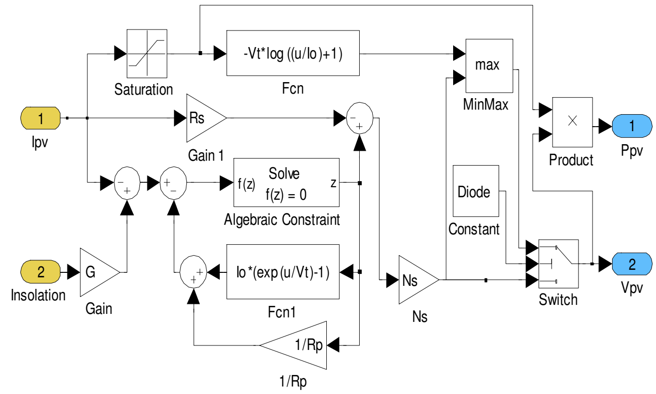

Figure 5. Simulink model of the PV module.

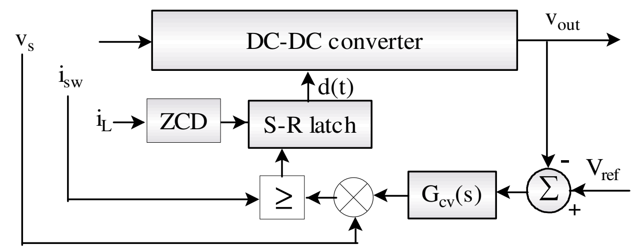

Figure 6. Hysteresis current control method for the control of the photovoltaic boost converter.

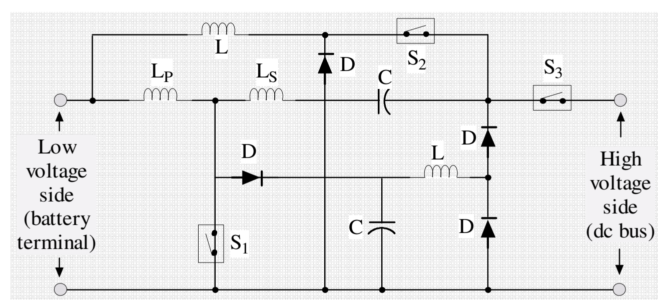

Figure 7. Bidirectional converter circuit diagram.

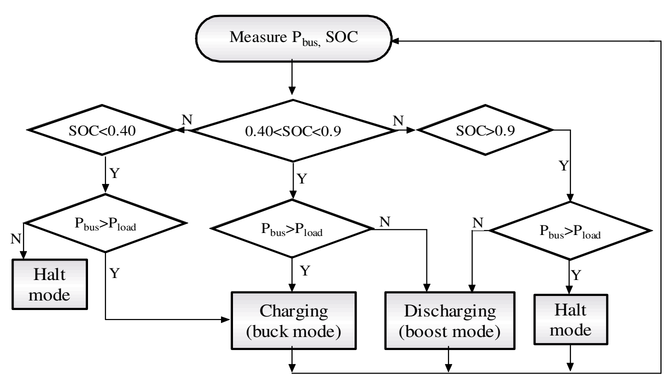

Figure 8. Bidirectional converter (battery charging/discharging) control algorithm.

E. Battery Model

A lead-acid battery model is used as per the system power requirements. The rated capacity of the battery model is set at 500 Ah. This rated capacity can support 2kW loads for approximately 32 hours according to Peukerts law defined by the equation,

$$C = I^{p} t \tag{6}$$

where, C is the battery capacity (Ah), I is the discharge current (A), P is the Peukert's constant and t is the discharge time (hour). For lead-acid battery, the value of P is between 1.1 and 1.3.

Battery type, initial state of charge and discharge characteristics can be set in this model. The lead-acid battery has discharging characteristics without exhibiting memory effect and superior life-cycle costs for the PV power system applications [19-21].

The charger regulates the state of charge of the battery within 40% to 90%, as the overcharging and deep-discharging of the battery may degrade the capacity and shorten the battery life-cycle. Infrequent or inadequate recharging can also cause over discharging symptoms called sulfation.

The choice between using more batteries operating at shallower discharge rates to extend the life of the batteries vs. using fewer batteries with deeper discharge rates and the correspondingly lower initial cost is considered carefully [22].

F. Inverter Control

The inverter converts the dc bus voltage to a regulated ac voltage with suitable amplitude and frequency. The output voltage and frequency have to be controlled as no grid exists in the stand-alone system. The filter ensures the ripple free power for the electrical appliances. The Pulse width modulation (PWM) technique is used to generate the switching pulses to drive the IGBT switches. Vector mode controller, as shown in Fig. 9, is used to regulate the required voltage and frequency of the inverter to support the load.

The vector control scheme used is based on a synchronously rotating reference frame as shown in Fig. 10. The angular velocity of the rotating axis system ω is set in the controller and defines the electrical frequency at the load. The voltage balance across the inductor L_f is given by

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_f \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \end{bmatrix} \tag{7}$$

where, L_f and R_f are the filter inductance and resistance respectively. v_{a1}, v_{b1}, v_{c1} represent voltages at the inverter output. i_a, i_b and i_c are the line currents.

The vector representation of a balanced three phase system and their equivalent vectors in a rotating *d-q* reference frame is shown in Fig. 10. Transforming the voltage equations using the *d-q* transformation in the rotating reference frame:

$$v_d = v_{di} - R_f i_d - L_f \frac{di_d}{dt} + \omega L_f i_q \tag{8}$$

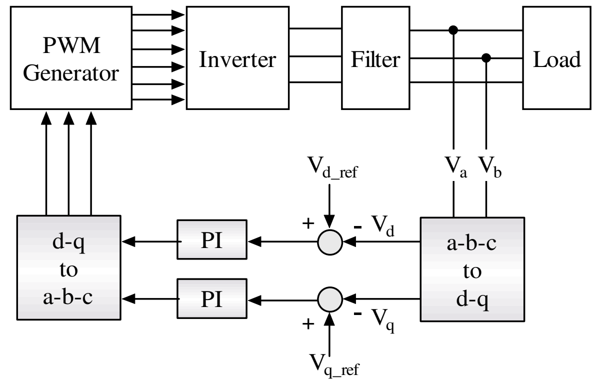

Figure 9. Vector control of inverter controller.

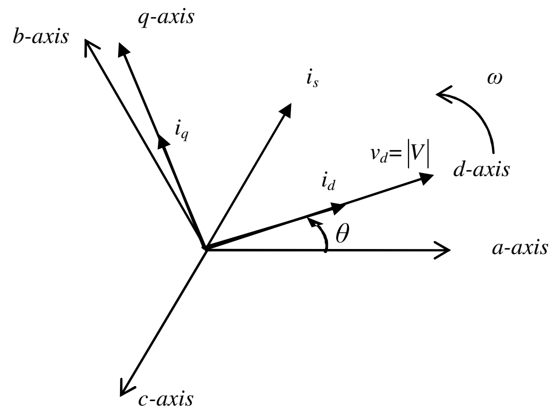

Figure 10. abc and rotating reference frame.

$$v_q = v_{qi} - R_f i_q - L_f \frac{di_q}{dt} - \omega L_f i_d \tag{9}$$

The instantaneous power in a three phase system is given by the equation,

$$P(t) = v_a i_a + v_b i_b + v_c i_c = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix} \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}' \tag{10}$$

Using the *dq* transformation, the active and reactive power is given by,

$$P = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \tag{11}$$

$$Q = \frac{3}{2}\left(v_d i_q + v_q i_d\right) \tag{12}$$

If the reference frame is as $v_q = 0$ and $v_d = |V|$, the equations for active and reactive power will be,

$$P = \frac{3}{2}\left(v_d i_d\right) = \frac{3}{2}|V| i_d \tag{13}$$

$$Q = \frac{3}{2}\left(v_d i_q\right) = \frac{3}{2}|V| i_q \tag{14}$$

Therefore, active and reactive power can be controlled by controlling direct and quadrature current components, respectively.

G. PI and PID controllers' tuning

PI and PID controllers are used at the different stages of the feedback loops in the hysteresis controller of the dc-dc converter and in the vector mode controller of the inverter. All of the PI and PID controller parameters of the control loops are tuned using Zeigler-Nichols tuning method and have chosen to obtain the best dynamic characteristics by considering the requirement of circuit stability and the possible operating conditions to meet the simulation system specifications [23].

III. RESULTS AND DISCUSSIONS

Simulation results show the voltages and currents at the different stages of the PV simulation system. Fig. 11 shows the inductor current and the output voltage of the dc-dc converter. The dc-dc converter gives the output voltage of around 380V at the dc link which is either processed by the inverter to support the load or fed through the bidirectional converter to charge the battery. As can be seen from Fig. 11, at the time of charging the battery, the dc link voltage goes down as more loads are imposed on the dc link. At this time, however, the voltage falls by 5% from the stable level. The hysteresis current control technique works well to stabilize the dc link voltage. Here, the inductor current through the converter is about 12A though it contains a high percentage of ripples. The limit of the converter current is important as it is used to estimate the rating of the switches and the values of the other parameters which are used in the converter circuit.

The terminal voltage and the state of charging and discharging of the lead-acid battery are shown in Fig. 12. The battery voltage remains almost constant at 48V during the discharging mode of operation. In the charging mode, however, it goes up to 68V. The battery charging and discharging is done uniformly within the specified limit of the state of charge. The charging and discharging of the battery depends on the battery capacity and the load demands. As the battery capacity is set to a higher value and the load is set to a lower value then it takes more time for the charging the battery than the discharging, and vice versa. The charger regulates the state of charge of the battery within 40% to 90%, as the overcharging and deep-discharging of the battery may degrade the capacity and shorten the life span of the battery.

As it is discussed earlier, the bidirectional converter acts as a buck-boost converter. During the charging time, it converts 380V of dc bus voltage to the battery terminal voltage of 48V. Whereas during the discharging time, the bidirectional converter boosts the 48V of battery terminal voltage to the 380V of dc link voltage. The current through the low and high voltage side of the bidirectional converter is shown in Fig. 13. The direction of the current through the bidirectional converter shows the charging and discharging modes of operation.

The output voltage of the inverter and the load voltage is shown in Fig. 14. The inverter output provides a 230 V rms voltage with 50 Hz frequency while 2 kW, 3-phase parallel RLC load is fed by the PV system.

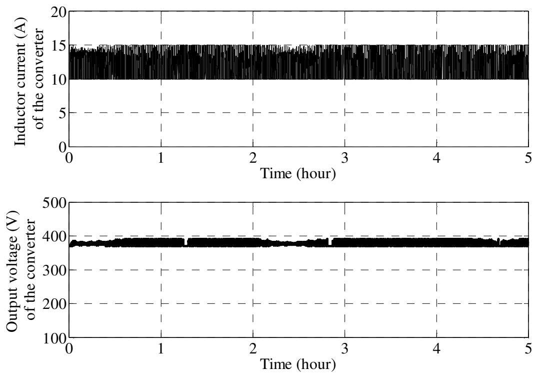

Figure 11. Current and voltage of the dc-dc converter.

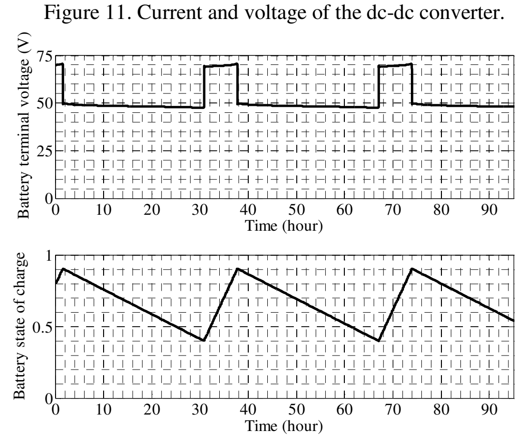

Figure 12. Voltage and state of charge of the lead-acid battery.

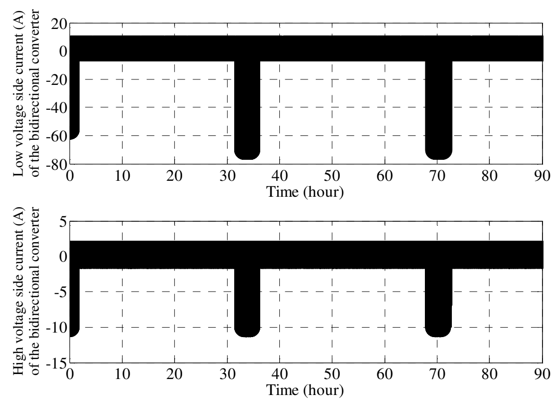

Figure 13. Current in the bidirectional converter at low and high voltage side.

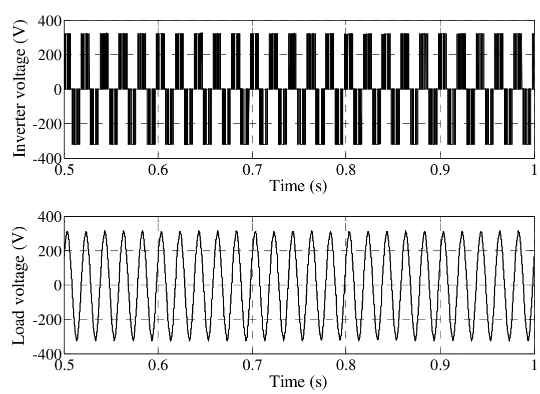

Figure 14. Inverter output voltage and load voltage.

IV. CONCLUSIONS

This paper presents an efficient control scheme for versatile power transfer among the PV source, the storage battery and the load. A high efficiency bidirectional converter-based battery charger control algorithm is designed for the effective management of battery charging and discharging. The bidirectional converter between the dc link and the battery ensures proper charging and discharging as well as secure control over the battery. The modes of operations of the battery charger are designed to make flexible management and to improve the reliability of the whole system through quick control incorporating the assessment of the dc link power and the battery state of charge. The supervision of the dc link power and the battery SOC makes the control scheme well-organized to manage safely the battery charger. The modeling and simulation of the system under the proposed control strategy is done with the Simulink/Simpower dynamic software simulation system. Simulation results are provided to justify the proposed control algorithm. The simulated system performs well with a 3kW PV source, a boost-type dc-dc converter, a buck-boost type bidirectional converter, a battery bank and a PWM IGBT inverter to support a 2kW RLC load. The hysteresis current control method is used to control the dc-dc converter and vector control method is used to control the inverter. A novel control strategy is proposed as the bidirectional converter-based battery charge controller. Simulation study confirms the feasibility and effectiveness of the control strategy and shows the successful coordination of the versatile power transfer. The proposed control algorithm is able to supply the dc link power effectively either to the load or to the battery according to the requirements, as well as to take power from the battery and to protect the battery from overcharging, and thus ensures a long life and an efficient management system for the battery.

TABLE I
SYSTEM SPECIFICATIONS

Subsystems	Specifications
PV module	3kW (peak), I_{sc}=5.45A, V_{oc}=22.2V
DC-DC converter	Boost, V_{in} = 180 ~220V, V_{out}= ~380V, Hysteresis current control switching, f_s=25kHz
Bidirectional converter	V_{low}= 48V, V_{high}=380V, Buck-Boost, PWM switching
Battery	48 V, 500 Ah, Lead-acid
Inverter	PWM IGBT inverter, V_{in}= 380V dc, V_{out}= 230V rms, 50 Hz
Load	2kW, Parallel RLC load

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