DESIGN OF GRID TIED BI-DIRECTIONAL INVERTER FOR BATTERY ENERGY STORAGE SYSTEM

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ABSTRACT

The main aim is to develop the Energy Management Control (EMC) with proposed Bi-directional converter. The EMC consists of a towering EMC level and a small EMC level. Bi-directional Inverter is skilled of connecting a battery bank with the Buck-Boost converters (BBC) provides high DC voltage gain and power density along with grid. Battery banks are interfaced by BBC. It operates two modes: a battery discharging mode and charging modes where current is fed into the grid and current drawn from the grid respectively. The charging and discharging modes are depending upon the Battery State of Charge (SOC). The mathematical analysis and simulation studies are given to validate the proposed system.

Keywords: Bi directional Inverter, Battery Energy Storage System, Grid Tied Inverter

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1. INTRODUCTION

On this modern world the need for electricity increases day by day. So, we need more power generation. The reduction in fuels and coal may affect the power generation. Renewable Energy Resource (RES) plays important role. The term RES includes solar power, Hydro and Wind power for power generation. Although RES power of generation is efficient, there some conflicts occur based on the maintenance of grid side voltages and frequency. For better power management, we go for Battery Energy Storage System (BESS). BESS governs the controlling and managing duty of the distributed generation units. It also protects load from various grid fault conditions. Energy storage system (ESS) is used for storing electric energy and release during the time of requirements. In our society for the future generation development this ESS becomes more important. ESS with RES plays major role in future development. The ESS will

rectify the issues with power grid. For grid tied storage system, BESS is more suitable among various ESS such as flywheel storage, thermal energy storage etc... Thus, the implementation of grid tied BESS increases the benefitable system for power generation.

Distribution System operation (DSO) are well supported by the BESS, which helps to rectify the problems caused due to distribution system growth, fluctuation and uncertain power generation from RES. The technical resolution such as power quality improvement, energy cost reduction, transmission and distribution networks investments changes and system service has been achieved by using BESS. By connecting battery module either in serial or in parallel capacity of the battery can be maintained.

The electrical grid is interleaved with an inverter which gets DC power from the BBC and convert it into the AC power. The grid frequency must be synchronized with the Grid -Tied Inverter (GTI). Each battery unit voltage must be coupled with the GTI. Hence it is combined to form the DC bus as input to the Buck -Boost converter (BBC). Although batteries are connected in series or parallel, several researches are made based on the converter and inverter connections.

In order to attain the battery equalization, the batteries are connected in parallel. Because of two-stage configuration the system complexity level is reduced, which also gives an easier system design. Due to increase in the current stress there will be reduction in the voltage at the converter side. Thus, inverter operates at two-stage will randomly reduce the efficiency. As soon as the efficiency decreases the capacity of the system also declines. The disadvantage in two-stage inverter configuration are reduced promisingly in Micro-inverter configuration because of power converting stage reduction. In Cascade -Inverter Configuration the battery module is connected along series formation.

2. PROPOSED GRID CONNECTED ENERGY STORAGE SYSTEM

The proposed method consist of GTI with Battery Energy Storage System (BESS) is shown in Fig 1. It contains a DC-DC converter which contains n-set of BBCs. At each BBC set encompasses with two switches which operates battery charging and discharging processes and two diodes are present for the freewheeling path of the current and an inductor enhance the current. This BBC receives DC current from the battery unit and convert it into a high frequency DC current. The BGI contains 4 switches namely S_p, S_p', S_q, S_q' . The switching frequency of these switches will be low. The Battery charging or discharging power command was achieved by GTI inverter. Single -Stage power conversion is the main aim of this GTI inverter as the power in each battery unit transfers to the grid. Efficiency of the system has been increases as reduction in the size of output inductor. As the battery State of Charge is as feedback, there is no need for current sensing unit. The circuit simplicity is simple for both discharging and charging modes. Each battery unit will be controlled by separate power control as this leads to several advantages like equalization of Battery Unit and flexibility can be achieved.

In this paper, the operation of the BG-inverter helps to improve the power flow control of each battery module system without current sensor. Similarly, it can also be adopted for different BMSs as long as the communication set of rules for the power flow command is determined by control circuit. In GTI each battery module has their own DC-DC converter and DC-AC inverter to control the output power which is realized by an output inductor and four active switches operated at AC main frequency as shown in Fig 1. It Produce a high frequency pulsating DC current with a sinusoidal envelope therefore, low battery and DC-bus voltages can be accomplished. DC-AC inverter accomplished to convert the high frequency pulsating DC current generated into a sinusoidal signal with line frequency. Because these inverters only switches at the zero crossing of the line voltage, its switching loss can be deserted by comparing to those power switches in the DC-DC converter. Therefore, the energy of each battery module

is transferred to the AC mains by single-stage power conversion. Because of the single – stage. power conversion operation, the power conversion efficiency can be improved significantly.

Figure 1 Proposed Grid tied inverter

For the BESS, current sensors are always needed. Conventionally, two current sensors, one for the BMS, which includes the State of charge (SOC) and temperature monitoring, and the other for the power converter, which realizes the current control capability, are demanded for the BESS.

The most commonly used energy storage component for the battery energy storage system are lead-acid battery and Li-ion battery. These components are selected based on the power density and battery life consideration. The sinusoidal current can improve the Li+ battery charging efficiency compared with the conventional constant-current and voltage charging strategy [12]. The battery efficiency and the life-time of the battery increases by using pulsating currents to charge and discharge the electrochemical battery power.

2.1. Discharging mode of operation with its control

The discharging mode of operation based on the principle that current will flows from battery into grid. This can be attained by two method of conversion namely (1) DC-DC (2) DC-AC. The battery voltage was boosted by the BBC converter and then the balanced DC was rectified into AC voltage by GTI. At this time of operation, the battery voltage must be higher that the capacitor voltage. GTI inverter is a Bidirectional inverter as current flows from battery to grid and vice versa. Between the Boost Converter and Bi-directional inverter there is no filter circuit. Hence the Unified voltage was fed into the Bidirectional inverter. At the output side of the GTI the filter circuit used to smooth the current inverter for the grid. It is an open loop control method thus the hardware implementation becomes easier. The pulse was generated by comparing reference signal. The circuit diagram for proposed BG inverter is shown in Fig.2. For firstBBC set the charging and discharging mode is discussed here. The BBC converter contains two switches namely C_{s1} and C_{s2} . The switch C_{s1} is turned on by generating gate pulse by comparing V_{sin} (sinusoidal signal) with V_{saw} (sawtooth carrier signal). The switch C_{s2} is off. Discontinuous mode of operation takes place during discharging period. i_{L1} is the inductor current.

During the half-cycle of the grid line, the overall switching N can be expressed as:

$$N = \frac{f_s}{2f_g} \quad (1)$$

Where, f_s is the switching frequency and f_g is the grid frequency

During the charging period for the first BBC set the input inductor L_a contains the active switch C_{s1} is turned on and the switch C_{s2} is always turned off. Thus, the voltage potential across the inductor L_a must be equal to the battery voltage V_{b1} , results in the linearly increase in the inductor current. When the switch C_{s1} is turned off, the voltage potential across the inductor L_a is reversed its path and equal to the capacitor voltage V_c which can be rectified as AC mains because of the DC-AC inverter. Due to the DCM operation, the inductor current i_{La} reduced to zero during the discharging period. The peak current of the input inductor of the n -th switching cycle can be expressed as:

$$i_{d_p1}[n] = \frac{V_c[n]}{L_a} (d_{d2}[n]T_s) \quad (2)$$

Where, $V_c[n]$ is the output capacitor voltage. As a result of the DCM SPWM control, (2) can be further modified as:

$$I_{d_p1}[n] = \frac{V_{b1}}{L_a f_s} D_{p1} \sin\left(\frac{n\pi}{N}\right) \quad (3)$$

To confirm the DCM operation in battery discharging mode, D_{p1} required to follow the following constraint:

$$D_{p1} < \left(\frac{\sqrt{2}V_g}{V_{b1} + \sqrt{2}V_g}\right) \quad (4)$$

Where, V_g is the rms value of grid line voltage.

It should be mentioned that the desired D_{p1} can be easily determined by controlling the amplitude of the V_{sin} . The average output current of the first BBC during the positive half-cycle can be derived as:

$$\langle i_1 \rangle = \frac{1}{N} \sum_{n=1}^N \frac{i_{d_p1}[n] d_{d2}[n] T_s}{2} \quad (5)$$

From (2) and (5), the average value of the output impedance can be expressed as follows:

$$\frac{\langle V_c \rangle}{\langle i_1 \rangle} = \frac{1}{N} \sum_{n=1}^N \frac{2L_a V_c^2[n]}{V_{b1}^2 d_{d1}^2[n] T_s} \quad (6)$$

In (6), the ratio of V_c and d_{d1} for each n -th switching cycle can be approximated as a constant since both of them can be approximated as rectified sinusoidal functions. It implies that BBC has a constant output impedance and can inject power into the ac mains with an almost unity power factor. Due to the DCM SPWM control, the average battery discharging power can be obtained as:

$$P_{b1} = \frac{V_{b1}}{2N} \sum_{n=1}^N i_{d_p1}[n] d_{d1}[n] \quad (7)$$

By Combining (2), (3), and (7), the expression of the average battery discharging power becomes:

$$P_{b1} = \frac{f}{L_a f_s^2} \sum_{n=1}^N (V_{b1} D_{p1} \sin\left(\frac{n\pi}{N}\right))^2 \quad (8)$$

From Eq. (8) it reveals that the average discharging power is only related to V_{b1} and D_{p1} . Therefore, the battery discharging power can be determined without measuring the battery current.

By measuring the battery voltage V_{b1} to generate appropriate maximum duty ratio D_{p1} of the BBC, it is possible to understand the individual power-handling capability required for the

BESS. Also, Eq. (8) denotes that the variation of inductance value will affect the accuracy of the output power of the grid.

2.2. Charging mode of operation and its control

In the charging mode, the Bidirectional BBC is used to buck the grid voltage to a level lower than the capacitor voltage coupled with the Bi-directional inverter so that current will be allowed to flow from the grid

Figure 2 Topology Configuration of proposed BG-inverter

into batteries. The inverter is used to step down the AC voltage from the grid into an unfiltered DC voltage. The chopped DC voltage is then passed into the batteries as a smooth current waveform. The charging mode uses freewheeling diodes on the DC-DC converter which regulates the amount of current that is allowed to flow into the batteries.

The BBC converter contains two switches namely C_{s1} and C_{s2} . The switch C_{s2} is turned on by generating gate pulse by comparing V_{ref} (reference signal) with V_{saw} (sawtooth carrier signal). The switch C_{s1} is off. Discontinuous mode of operation takes place during charging period. i_{L1} is the inductor current. During the charging period for the first BBC set the input inductor L_a contains the active switch C_{s2} is turned on and the switch C_{s1} is always turned off. Thus, the voltage potential across the inductor L_a must be equal to the capacitor voltage V_c . When the switch C_{s2} is turned off, the voltage potential across the inductor L_a is reversed its path and equal to the battery voltage V_{b1} . Due to the DCM operation, the inductor current i_{L_a} reduced to zero during the discharging period. The peak current of the input inductor of the n -th switching cycle can be expressed as:

$$I_{c-pl} = \frac{V_c}{L_a} (D_{c1} T_s) = \frac{V_{b1}}{L_a} (D_{c1} T_s) \quad (9)$$

Also, to ensure the DCM operation in battery charging mode, D_{c1} must follow the following restriction:

$$D_{c1} < \left(\frac{V_{b1}}{V_{b1} + \sqrt{2} V_g} \right) \quad (10)$$

As a result of the DCM SPWM control, the average battery charging power can be attained as:

$$P_{b1} = \frac{f_{Dc1}^2}{L_a f_s^2} \sum_{n=1}^N (V_c)^2 \quad (11)$$

From Eq. (11) we can know that the ordinary battery charging power is simply related to $V_c[n]$ and D_{c1} . By using the battery State of Charge (SOC) both the charging and discharging modes of operation has been obtained.

3. CONTROL SCHEME FOR BG INVERTER

A Control circuit controls the power module system. The BMS generates discharging/charging(D/C) and power commands P_{b1} and directed to the controller of the BG-inverter. The duty cycle signals, D_{p1} for discharging and D_{c1} for charging, can be generated by using the derived equations (8) and (11). The gate pulse of C_{s1} can be generated by comparing $D_{p1} \sin \omega t$ with the saw-tooth carrier signal V_{saw} . Also, the gate pulse of C_{s2} can be made by comparing D_{c1} with the saw-tooth carrier signal V_{saw} .

DC-AC inverter is realized by four active switches which are operated at minimum switching frequency. It can convert the high frequency pulsating DC current generated by the BBCs into a sinusoidal signal with utility line frequency. During the positive half-cycle of the AC mains, the switches of the inverter S_p and S_q are switched-on while S_p and S_q are turned off. Where at negative half-cycle, switches S_p and S_q are switched on and S_p and S_q are switched off. GTI consists of four active switches connected with AC mains, its switching loss is very low and can be neglected. Therefore, the proposed BG-inverter only has one high-frequency PWM signal and can be categorized as a single-stage inverter. The required synchronization signal for the interleaving operation can be obtained from the AC line voltage and no extra communication between BBC is required.

The shifting time T_{sm} of m-sets of BBCs can be expressed as:

$$T_{sm} = \frac{1}{mf_s} \quad (12)$$

Since the average voltage of output inductor L_c is zero at steady state, the average voltage across C is equal to V_g and the peak discharging time T_{off} can be expressed as:

$$T_{off} = \frac{V_{b1} D_{p1}}{\sqrt{2} V_g f_s} \quad (13)$$

The discharging time of the capacitor C can be expressed as:

$$T_d = T_{sm} - T_{off} = \frac{1}{mf_s} - \frac{V_{b1} D_{p1}}{\sqrt{2} V_g f_s} \quad (14)$$

The peak voltage deviation of the output capacitor C can be obtained as:

$$\Delta V_c = \frac{T_d I_g}{C} \quad (15)$$

Where, C determines capacitor value and I_g determines peak value of the output current.

Figure 3 Control scheme for one BBC set

The stored energy in the output capacitor varies in accordance with the stored energy in the output inductor at T_{sm} interval, Thus the stored energy equation can be derived as:

$$E_d = \frac{1}{2} C \Delta V_c^2 = \frac{1}{2} L_c \Delta I_c^2 \quad (16)$$

Where, L_c determines output inductor value.

The peak current deviation of the output inductor can be obtained:

$$\Delta I_c = \sqrt{\frac{\left(\frac{1}{mf_s} \frac{V_{b1} D_{p1}}{\sqrt{2} V_s f_s}\right)^2}{L_c C}} \quad (17)$$

The charging time T_{on} can be expressed as:

$$T_{on} = \frac{D_{c1}}{f_s} \quad (18)$$

The charging time of the capacitor C can be stated as:

$$T_{on} = T_{sm} - T_{on} = \frac{1}{mf_s} - \frac{D_{c1}}{f_s} \quad (19)$$

The output capacitor peak deviation can be derived as:

$$\Delta V_c = \frac{T I_g}{C} \quad (20)$$

From Eq. (16), (19), (20), the output inductor L_c at peak current deviation is given by:

$$\Delta I_c = \sqrt{\frac{\left[\left(\frac{1}{mf_s} - \frac{D_{c1}}{f_s}\right) (I_g)\right]^2}{L_c C}} \quad (21)$$

4.SIMULATION MODEL AND ANALYSES

The simulation studies and analysis for this system was developed using MATLAB/Simulink. The desired output power can be achieved by setting the component parameters in match with the previously solved divisions. For the 230V/50Hz power line, the battery unit specifications are listed in Table I. From Eq. (9), the maximum duty ratio for battery discharging mode is given by:

$$D_{p1} = 0.964 \quad (22)$$

From Eq. (10), the duty ratio for charging mode is given by:

$$D_{c1} = 0.035 \quad (23)$$

The simulation results during discharging mode is presented *here*, the switch C_{s2} is off and C_{s1} generated gate signal by the comparison of V_{sin} with V_{saw} at discontinuous current mode. During discharging operation, the inductor which gains energy from battery and discharge to grid. Its current path is from positive to negative, hence its waveform is only in positive cycle.

The inductor which gains energy from grid and charge the battery module system during charging operation. Its current path is from negative to positive; hence its waveform is only in negative cycle as reverse direction. The inverter output for 230V/50Hz is shown in Fig1.9. The simulation result during charging mode are presented *here*, the switch C_{s1} is off and C_{s2} generated gate signal by the comparison of V_{ref} with V_{saw} with discontinuous current mode

Table 1.2 Specifications of proposed BG-inverter

SPECIFICATIONS	RANGE
Nominal capacity	100Ah
Battery voltage	12V
Maximum charging voltage	16V
Cut-off voltage	12.4V
Standard charging current	1C
Standard discharging current	1C
Maximum discharging current	750A(5sec)

Table 1.2 Specifications of battery

TERMS	RANGE
Input inductor L_a & L_b	178 μ H
Battery module voltage V_{b1}	50V
AC mains	230Vrms/50Hz
Switching frequency f_s	20kHz
Output capacitor C	2 μ F
Output inductor L_c	1.5Mh

Figure 4 (a) Pulse generated for switch C_{s1}

(b) Inductor current

The battery state of charge (SOC) is set to 100 percentage during discharge operation.

Figure 5 Battery waveforms for 100% state of charge

The inverter output for 230V/50Hz voltage is shown in Fig1.6

Figure 6 (a)output voltage of AC inverter

(b) output current of AC inverter

Figure 7(a) Pulse generated for switch C_{s2}

(b) Output current of inductor

The battery state of charge is set to 10 percentage during discharge operation

Figure 8 Battery waveforms for 10% state of charge

Figure 9(a) output voltage of AC inverter

(b) output current of AC inverter

The capacitor voltage connected along the BG inverter as the inductor is related with the capacitor voltage for each mode of operation. The iL_1 is compared with the capacitor voltage, for discharging mode of operation L_a should be equal to V_c and for charging mode of operation same as L_a should be equal to the battery

Figure 9 (a) FFT range for output current

(b) Capacitor voltage

5. CONCLUSION

The proposed BG-inverter governs each battery module during both charging and discharge by using control of pulsating current. The batteries get charge from the AC mains likewise the current also given to the ac mains. The discontinuous waveform of current was caused by the inductor. Thus, the bidirectional flow of power has been achieved. The single-stage operation increases the efficiency of power conversion. By using MATLAB/ Simulink, simulation results of the system were analyzed, and it proves that the proposed system rises the role of ESS.

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