Effective Battery Management in FPGA based DC SPV System through Closed Loop Bi-Directional DC-DC Converter for Energy Storage

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Abstract- In this present scenario of power generation, solar PV systems became very popular to generate electrical energy for remote locations and no grid interaction. For this type of systems, battery storage is must to store the electrical energy and stored electrical energy is used to feed the loads during night and cloudy days. In this paper a converter is proposed to charge the battery during day time and discharge the battery during sun unavailable time through the same converter, Bi-directional DC-DC converter (BDC). Proposed Bi-Directional DC-DC converter (BDC) is operated in two modes of operation namely buck mode for charge the battery and boost mode of operation for discharge the battery to feed the stored energy to loads. An electronic controller is designed in FPGA kit to select the mode of operation of BDC. Since BDC converter transfer function is of second order in either mode, PID controller is preferred to control BDC in buck mode and Type-3 controller is preferred in Boost mode in order to achieve better control the Power flow. Voltage Mode PWM technique is used to control the BDC in either mode. All the controllers (mode selection and Type-3) are implemented in digital domain for the direct implementation in FPGA. In this proposed study, BDC controllers are design from small signal analysis of dc-dc converters, Solar PV (Solar PV module and MPPT based charge controller) system design and their simulations have been presented. Computation evaluation for proposed system has been done on MATLAB simulink and XILINX system generator flat forms.

Keywords: SPV System, MPPT Charge controller, FPGA, Type-3 controller, Bi-Directional DC-DC Converter, Buck converter, Boost Converters.

1. INTRODUCTION

As on today still many of the villages in the world have no access of grid because of many reasons like the villages which are located hilly areas, far away from grid locations and icy locations etc. Standalone solar PV system became a best choice for that type of off gird villages. The essential part of that type of renewable energy system is a storage element, to store the surplus energy and stabilizes the output during the period of power shortages. Mainly energy storage element is must in standalone solar PV systems to provide uninterruptable power during cloudy days and night times.

In this paper renewable energy systems include an energy storage element charged by the BDC is used to improve the power quality. Basically DC-DC Converter has unidirectional power flow capability, however a unidirectional dc –dc converter can be turned into bi-directional dc-dc converter by replacing diode with its controllable switch in its structure which allows the power transmission between two dc sources in both the directions [1-2]. DC-DC Converters are employed in various applications including power supply for personal computers, office equipment, spacecraft power systems, laptop computers and telecommunications equipment as well as hybrid vehicle, fuel cell vehicle and renewable energy system.

As per the literature [3-4] there are different types of topologies are used to design the BDC. However those topologies leads to increase the complexity and size of the system, high amount of ripples in load current, causes decrease in efficiency.

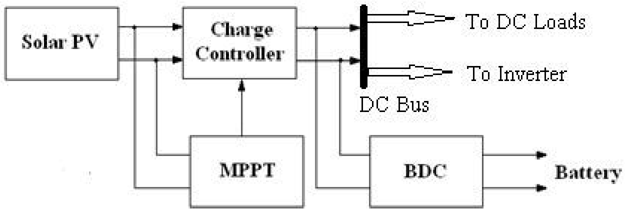

Figure 1.Proposed System of BDC

Block diagram of proposed system is shown in figure1. In this proposed study, 150watt solar PV modules are modelled at 24.2V dc output voltage at STC conditions by connecting 50 solar cells in series. According to the nature of solar photovoltaic cells, the out voltage and currents of the modules are variable DC type since those are function of solar irradiation and temperature. This module will produce maximum power at one unique operating point. To operate the module at that operating point charge controller with MPPT algorithm is need to be designed. MPPT charge controller is designed with the conversion capability of 24.2V to 200V to create DC bus at higher voltage to convert ac voltage or feed some loads. The proposed BDC converter is developed with conventional topology. Designed topology offers the following advantages like less complexity and size of the system, and increase its efficiency beside improves the performance of the system. Generally BDC act as interfacing medium between two different voltage levels DC buses (High level DC bus and low level DC bus). In the proposed system solar PV side bus is at higher voltage level and battery side voltage at lower DC voltage level. Based on input condition (Irradiation level and temperature) BDC mode of operation will be decided and the BDC will be operated either as buck mode or boost mode. In each mode, DC-DC converter requires separate controllers for its closed loop operation. These controllers have been designed with the help of small signal analysis of DC-DC converters. All these controllers have been designed in digital domain for the implementation in FPGA.

II. PROPOSED SYSTEM CONFIGURATION

The block diagram for the projected system as shown in the figure.1 is a standalone PV system. In this system, the key elements are solar PV module, MPPT based boost converter and Bi-direction DC-DC converter and energy storage element (battery). Ambient solar energy extraction, utilization and storage are the objective of this paper. To extract and conversion of ambient solar energy into electrical energy, solar PV module are the choice.

A. Solar PV module:

Solar PV cell is a primary element in conversion process of solar energy into electrical energy. But these cells are producing voltages at very low level (normal range is 05-0.6V). Hence solar PV cells are connected in series to form solar PV module. Solar PV module equivalent is shown in below figure.2.

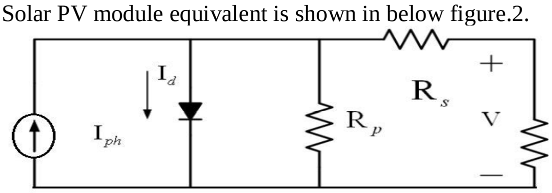

Figure2. Practical model of solar cell

From this it is clearly understand that solar PV module equivalent circuit consists a current source, diode, shunt resistance, series resistance and load. This current source generates current with the magnitude of

Photon Current $(I_{ph}) = I_{sc}(1 + \alpha\Delta T)\frac{G}{G_o}$ (i)

Here I_{sc}=Short-circuit current due to sunlight, G = irradiance level of solar PV module, G_o = irradiance at Standard test condition (1000W/m^2), ΔT = T-$T_{ref,}$ T = Temperature of module (^{o}C), T_{ref} = Temperature at standard test conditions

$$\alpha = 0.0012 \times I_{sc}$$

It is evident that generated photon current is function of temperature (T) and irradiance (G) from equation (i).

And the load current $(I) = I_{ph} - I_d\left\{e^{\frac{V_d}{A*V_T}} - 1\right\} - \frac{V_d}{R_p}$ (ii)

Here I_d=Current shunted through the diode;

Diode Voltage $V_d = V + IR_s$ (iii)

Thermal voltage (V_T) = $\frac{K*T}{q}$ (iv)

R=Load resistance;V=Voltage on the load;R_s=series resistance;R_p=Shunt resistance;q=Electron charge (1.602e^{-19}C); K=Boltzmann's constant;

Equation (ii) states that the relationship between solar PV module voltage and current is non-linear. And also it is clear that output current is varies with the changes in temperature and/or irradiation. Their solar module PV power characteristics under variable irradiation and temperature for BPsx 150 are shown in below figures 3 and 4.

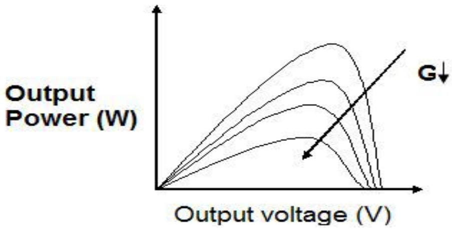

Figure3. Output P-V characteristics of solar PV module with varying G

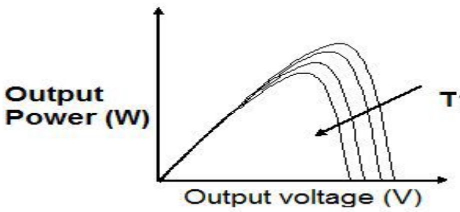

Figure 4. Output P-V characteristics of solar PV module with varying T

From these characteristics, it is evident that solar PV module is having unique operating point for the optimal operation. To extract maximum power from module, load resistance must be matched with source resistance. But according to nature of solar PV module, module output voltage and currents are function of irradiance and temperature as shown in the equation (ii). When solar module voltage and currents are varying with non linear relationship obviously module resistance will vary. Hence there is a necessity of some interfacing track which can match module resistance and load resistance under such type of varying temperature and irradiance conditions. After done a lot of research on it the researchers found a circuit called MPPT based charged controller.

B. MPPT based charge controller:

As mentioned earlier, MPPT charge controller act as interfacing circuit between solar module and DC bus. The role of this circuitry is to extract the maximum power from modules such a way that overall efficiency of the system can be increased. Basically MPPT charge controller is nothing but a power electronics dc-dc converter circuit with MPPT algorithm. There is a many literature is available for these MPPT controllers. In this proposed study P & O method incorporated in boost converter has been adopted for the design of MPPT charge controller.

B.i. Open circuit voltage MPPT algorithm:

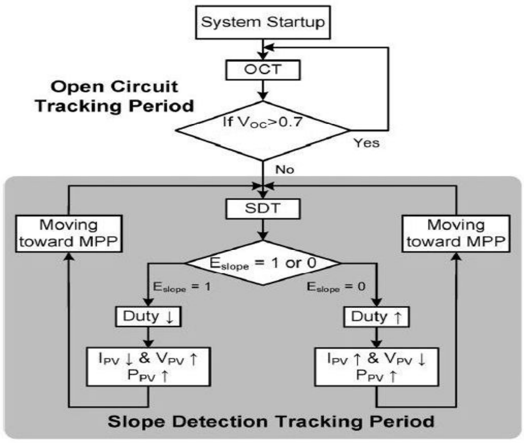

Figure 5. Flowchart of MPPT control algorithm

The Open circuit voltage MPPT algorithm is very famous technique for maximum power tracking of solar power from solar PV modules. The algorithm used in this method shown in following figure 5.

B.ii. Boost Converter:

This boost converter, which is part of MPPT charge controller, is controlled with duty cycle coming from P&O method. The output of boost converter voltage and currents are constant and willcreate a DC bus. This DC bus can be used to feed DC loads and/or Inverters as shown in figure 1. In this paper parallel path (with respect to inverter path) has been provided for the battery throughBi Directional DC-DC converter. Operation of boost converter is explained in section C.ii.

C. Bi-Directional DC-DC Converter:

It is belongs to the category of DC-DC converter family. It is basically a one DC-DC converter under the consideration of circuit with two modes of operation namely buck mode and boost mode. Based on the availability of solar energy BDCmode can be selected i.e. boost mode or buck mode. Based on availability of sun power mode will be selected there by decides thedirection of power flow.During day time,BDC will operate as a buck converter mode which charges the battery from the available solar energy hence power will flow from solar system to load end. In the other mode of operation,it will operate as a boost converter in which battery supplies the power required by the load causes power will flow from battery to source end.

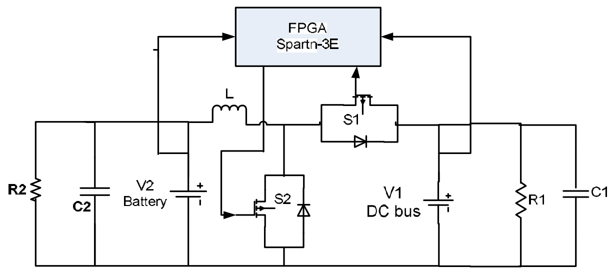

Figure 6. Circuit diagram of BDC

Operational Modes of BDC:

1. Buck Mode
2. Boost Mode

These Operations will be selected as follows

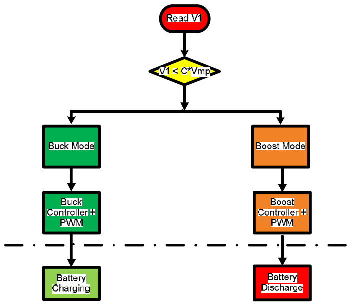

Figure 7: Operational Mode Selection

D. i. Buck Mode Operation:

Figure.8 shows the operational circuit of BDC Converter which is working as a buckmode. In this mode of operation the available solar energy from the modules is used to charge the storage element. Pulse width modulation (PWM) control is used to control the power switch (MOSET) intermittently to operate in between saturation and cut-off states. In this mode of operation when the power switch (MOSFET) is in ON state causes the input potential V_{in}will applied across the inductor tends to increase which is flowing through the current. When the power switch (MOSFET) is in OFF state the inductor will act as source and current is flowing continuously through the diode. But here the outputvoltage is lesser than input voltage hence this converter is known as step-down converter.

The change in the inductor current can be analyzed by changing the input voltage from V_x to V_2 in the circuit.

The voltage and current relation of an inductor is given by:

$$V_x - V_2 = L \, di/dt$$

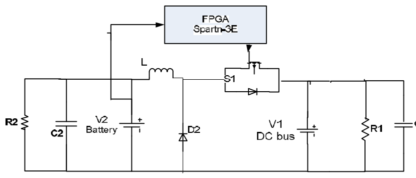

Figure8. Circuit Diagram of Buck Converter

The change in inductor current should satisfy the relation given below:

$$di = \frac{1}{L}\left\{ \int_0^{t_{on}} (V_x - V_2)dt + \int_{t_{on}}^{T} V_x \right\}$$

The inductor current should not change during the period T under steady state condition to satisfy volt-ampere's law. Therefore during turn ON time of the MOSFET, $V_x = V_1$ and during turn OFF time $V_x = 0$

Hence,

$$0 = di = \int_0^{t_{on}} (V_1 - V_2)dt + \int_{t_{off}}^{t_{on}+t_{off}} (-V_2)dt$$

This further shortens to $(V_1 - V_2)t_{on} - V_2 t_{off} = 0$

$$\frac{V_2}{V_1} = \frac{t_{on}}{T}$$

Where D is "duty ratio" and it is given as $D = \frac{t_{on}}{T}$

In the lossless condition the relationship between input and output voltage becomes $V_2 = D * V_1$ and the average power can be $V_2 * I_2 = V_1 * I_1$. Therefore average current must be $I_1 = D * I_2$. All those above relations should satisfy only when the current following through the inductor will not become zero.

D.ii. Boost Converter:

With the intermittent nature of renewable resources the energy generation to meet the demand all the time is very difficult. Due to this effect if the input voltage level is very low to meet the demandof load at DC bus, then this converter (BDC)will increase the voltage level by utilising the energy stored in the storage element i.e., battery. The proposed converter during this state is operated as a step-up converter. Figure9 represents the circuit diagram of the boost converter, when the power switch (MOSFET) is in ON state the diode is reverse biased which causes the isolation of output stage from the input stage and the current which flows through the inductor will increase linearly. Then the voltage relation become $V_x = V_2$. Conversely when the power switch (MOSFET) is in OFF state the diode is forward biased because the energy stored in the inductor will pass through the diode which causes the output stage will receive energy from the input stage. Then the voltage relation becomes $V_x = V_1$.After the study of this operation mode, the inductor current remains flow continuously. Fig 11 represents the wave forms of inductor voltage average must be zero for the average current to remain in steady state.

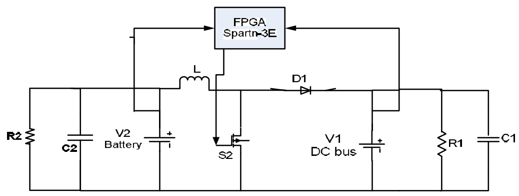

Figure-9 Circuit Diagram of Boost converters

$$V_2 * t_{on} + (V_2 - V_1)t_{off} = 0$$

So, $$\frac{V_1}{V_2} = \frac{T}{t_{off}} = \frac{1}{1-D}$$

And the power is balanced for the lossless circuit results $\frac{I_2}{I_1} = (1 - D)$

From the above showed a relationship it is observed that when duty ratio is varies between 0 and 1, the magnitude of output voltage is greater than the input.

C. Voltage Mode Control:

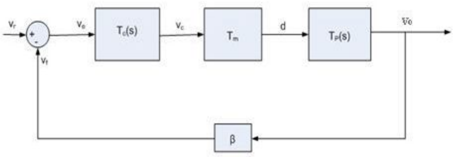

Figure 10. Closed loop control of DC-DC Converter Block Diagram Representation

Open loop output voltage of DC-DC converter (Vo) is step down to feedback voltage (V_F) by feedback factor ($\beta = \frac{V_o}{V_F}$) and V_F is compared with fixed reference voltage V_R, produces error voltage V_e. Error Voltage is corrected by the double-lead controller $T_c(s)$ and it produces the control voltage V_c. Pulse width modulator Tm compares the fixed frequency saw-tooth voltage V_{saw} with the control voltage and produces the required duty ratio D.

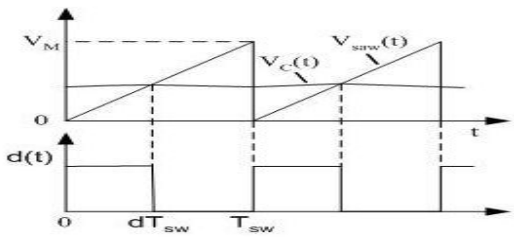

Figure-11 PWM Voltage mode control method

The DC-DC converter plant Tp(s) gives desired output voltage VO corresponds to the corrected duty ratio produced by modulator. The double lead integral controller has been designed and implemented on FPGA spartan-3 XC3S5000.

E. FPGA (Field Programmable gate array):

A field-programmable gate array (FPGA) is an integrated circuit designed to be configured by a customer or a designer after manufacturing—hence "field-programmable." An FPGA is a field programmable device suitable for switching application in power electronics. It can be easily programmed to design a pulse width modulator (PWM) for control applications. Further its fast switching capability and easy implementation of soft computing algorithms make it preferred choice for power control system application and power quality. In this proposed work, the BDC converter will be implemented on FPGA after the simulation in MATLAB.

III. SIMULATIONS & DISCUSSIONS

To simulate proposed system, BPsx150 solar module was modelled in MATLABSimulink environment with following data as shown in table 1.

Table 1. Datasheet values of solar PV module

Data Sheet Values		Estimated Parameters	
I_{sc}(Short circuit current)	7.36A	I_{ph}(Photon current)	7.36
V_{oc} (Open circuit voltage)	30.4V	I_o(diode current)	$0.104e^{-6}$A
V_{mpp} (Voltage at maximum power)	24.2V	A (Diode factor)	1.310
I_{mpp}(Current at maximum power)	6.83A	R_s(series resistance)	0.251ohm
n_s(No. of Series connected solar cells)	50	R_{sh}(Shunt resistance)	1168ohm
Temperature Coefficients			
K_i(Temperature Coefficient for current)	0.057%	K_v(Temperature Coefficient for voltage)	-0.346%

After modelled solar PV module in MATLAB 2012b simulink different characteristics (power Vs Current & current Vs voltage) for different irradiation levels have been plotted and shown in figure 12 and 13.

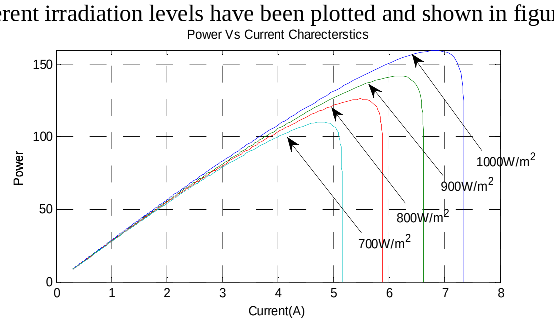

Figure 12: PI characteristics of solar PV module

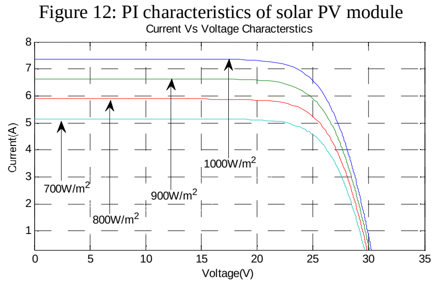

Figure 13. VI characteristics of solar PV module

In this proposed study 160watt solar PV modules are modelled with 24.2V dc voltage at maximum power point under STC conditions by connecting 50 solar cells in series.And 3 solar PV modules are connected together in parallel mode to get form one array of 480W and then these arrays connected in series to get 960Watt. This output voltage is of fed to MPPT based charge controller in order to extract maximum power from solar PV module. The design of that MPPT boost converter of constant voltage mode designed for 480W with following specifications for each array.

Input voltage = 24.2V, Output Voltage = 200V, duty cycle D = 0.88, output power = 480, Switching frequency = 20 KHz, converter output current = 2.4A.

Selection of components for Boost converter with their parasitic component values

MOSFET with rDS = 0.18,Inductor (L) = 700µH,ESR of Inductor rL = 0.1900,Capacitance C = 1.47e-4,ESR of Capacitor rC= 0.111,Diode on-state resistance RF = 0.0720,Total parasitic resistance with the inductor at D (r) =0.3322

Plant transfer Function of Boost Converter:

$$\frac{-0.855s^2 - 4.172e^4 s + 6.544e^8}{s^2 + 564.6s + 1.145e^6}$$

Controller Transfer function for Boost converter:

$$\frac{1.313e^5 s^2 + 9.321e^7 s + 1.654e^{10}}{s^3 + 2.582e^4 s^2 + 1.677e^8 s}$$

Controller design is verified with the help of frequency response analysis i.e. Bode plot is plotted for DC-DC converter loop gain and shown in figure 14.

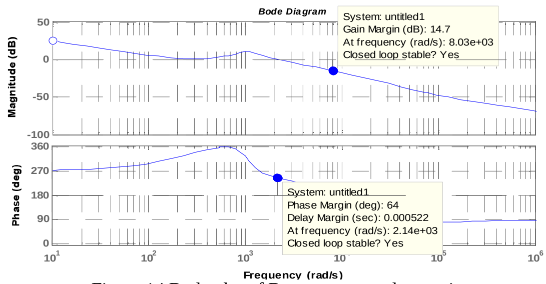

Figure 14.Bode plot of Boost converter loop gain

Figure.14 depicts the frequency domain specifications of DC-DC boost converter as follows.

Phase Margin = 64^o and Gain Margin = 14.7dB gives idea that the designed converter is fully stable. The output voltage and currents of boost converter are shown in figure 15.

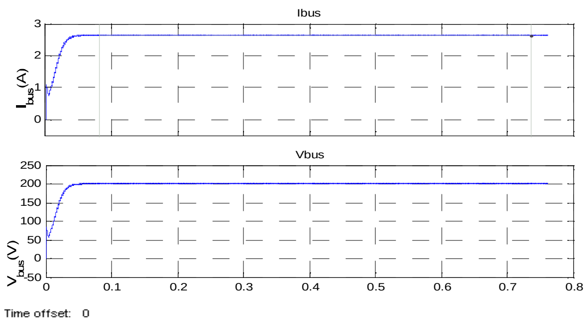

Figure 15. Boost Converter output current and voltage

As mentioned above two solar arrays fed MPPT charge controller are connected in parallel and created DC bus with 200V and 960W rating. This bus is used to feed power to DC loads directly, AC loads indirectly means through inverter and charge the battery through BDC. To charge battery Bi-Directional DC-DC converter (BDC) is designed with power flow direction in both the ways between 24V (battery) and 200V (DC bus) voltage levels. In the presence of sun battery gets charged and will be discharged during no sun time. Designed BDC response waveforms are shown in following figures.

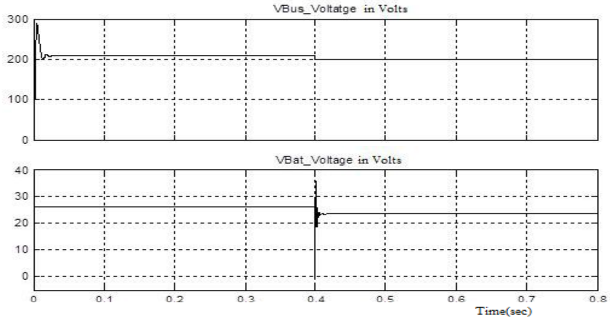

Figure 16. Voltage waveforms of BDC either sides (Bus side and battery side)

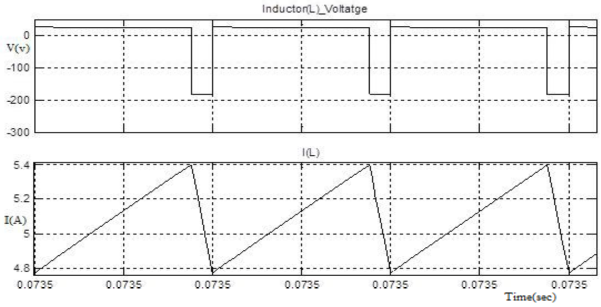

Figure 17. Inductor voltages and currents of BDC

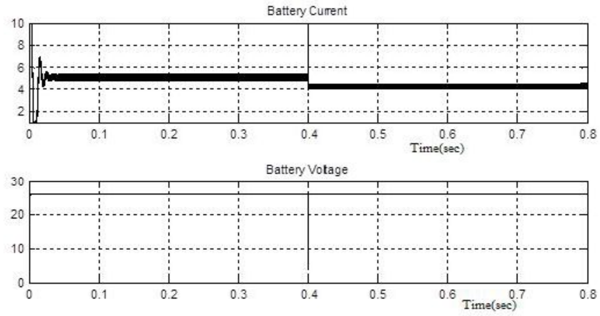

Figure 18. Battery side voltage and current

IV. CONCLUSION

This study presented a Battery interfacing with FPGA based DC SPV system through Closed Loop Bi-Directional DC-DC Converter for solar energy storage. For this study, modelling and simulation of solar PV module, MPPT based charge controller, closed loop Bi-directional DC-DC converters and their integration as a proposed system have been done in MATLAB Simulink and system generator environment. After done computational simulations for proposed system in MATLAB Simulink and Xilinx system generator environments it can be clearly concluded that the battery is charging during sun time and discharging during no sun time taking place with very low ripple batter voltage content. And designing of controllers for boost and BDC have been implemented with Xilinx system generator tool have been interfaced with power circuit in MATLAB. All these dc-dc converters are offering very good performance for line and load variations with the following frequency domain specifications such as PM=64 and GM=14.4dB. With this proposed system simulations, it can be concluded that effective management of charging of energy storage element (battery) during sun time and discharging during no sun time is confirmed.

REFERENCES

[1] Arezki, S.; Boudour, M., "Simulation and modeling of a photovoltaic system adapted by a MPPT control reaction: Application on a DSIM," *Energy Conference and Exhibition (EnergyCon), 2010 IEEE International* , vol., no., pp.423,428, 18-22 Dec. 2010

[2] Kokaew, V.; Moshrefi-Torbati, M.; Sharkh, S.M., "Simulation of a solar powered air compressor," *Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on* , vol., no., pp.1,4, 8-11 May 2011

[3] Raveendhra, Dogga.; Pathak, M.K.; Panda, A.; "Power conditioning system for solar power applications: Closed loop DC-DC convertor fed FPGA controlled diode clamped multilevel inverter," *Electrical, Electronics and Computer Science (SCEECS), 2012 IEEE Students' Conference on* , vol., no., pp.1-4, 1-2 March 2012.

[4] O.Wasynczuk, "Dynamic behavior of a class of photovoltaic power systems," *IEEE Trans. Power App. Syst.*, vol. 102, pp. 3031-3037, Sept. 1983.

[5] J. A. Gow and C. D. Manning, "Development of a photovoltaic array model for use in power-electronics simulation studies", Electric Power Applications, IEE Proceedings, 146(2):193–200, 1999.

[6] N.Femia, G.Petrone, G.Spagnuolo, and M.Vitelli, Optimization of perturb and observe maximum power point tracking method," *IEEE Transactions on Power Electronics*, 20 (4), 963–973,2005.

[7] Abraham .I. Pressman, "*Switching Power Supply Design*", Tata McGraw-Hill publications, 1991.

[8] M. K. Kazimierczuk and R. C. Cravens, II, Close-loop characteristics of voltage-mode controlled PWM boost dc–dc converter with integral-lead controller. *Journal of Circuits, Systems, and Computers*, vol. 4, no. 4, pp. 429–458, 1994.

[9] Busquets-Monge, S.; Rocabert, J.; Rodriguez, P.; Alepuz, S.; Bordonau, J.; , "Multilevel Diode-Clamped Converter for Photovoltaic Generators With Independent Voltage Control of Each Solar Array," *IEEE Transactions on Industrial Electronics*, vol.55, no.7, pp.2713-2723, July 2008.

[10] Raveendhra, Dogga.; K.P.G Swamy; Padmanabh Thakur, "FPGA based 2-stage power conditioning system for PV power generation," IEEE International Conference on Power, Energy and Control, 6-8 February2013, India.

[11] Dogga. Raveendhra, B.L.NarasimhaRaju, Padmanabh Thakur, "Design and Small signal analysis of solar PV Power Conditioning system fed FPGA Controlled Bi-Directional DC-DC Converter "IEEE International Conference on Circuit, Power and Computing Technologies, 2013 21st&22nd March, India.