Available Online at www.ijcsmc.com

International Journal of Computer Science and Mobile Computing

A Monthly Journal of Computer Science and Information Technology

ISSN 2320–088X

IJCSMC, Vol. 4, Issue. 11, November 2015, pg.57 – 63

RESEARCH ARTICLE

Design and Simulation of a Solar Based DC-DC Converter for Hybrid Electric Vehicles

Sandu Sridevi[1], P. Varaprasad Reddy[2]
[1]M.Tech Student (PE&D), Vignana Bharathi Institute of Technology, Hyderabad
Email: sridevi14sri@gmail.com
[2]Assistant Professor, EEE Dept., Vignana Bharathi Institute of Technology, Hyderabad
Email: varaprasad.vbit@gmail.com

Abstract--This paper presents modeling, design and analysis of a bidirectional half-bridge DC/DC converter suitable for power electronic interface between the main energy system and the electric traction drive in hybrid electric vehicles. A solar based renewable energy system is considered as input. A parallel dc-linked multi input converter with a half-bridge bidirectional DC/DC cell topology is chosen to link the solar energy system with the dc-link. The paper focuses on modeling the proposed converter for steady state analysis. Averaging and linearization techniques are applied to obtain the averaged state space models and small signal models of the converter in both boost and buck operation modes. A criterion for sizing the converter passive components based on the imposed design specifications and constraints is illustrated. Simulation results of the buck-boost converter during normal functioning are presented. The same compared with the performance of DC-DC converter for the input of hybrid energy storage system which consists of battery and ultra-capacitor.

Keywords: Bidirectional DC/DC converter; hybrid electric vehicles; dynamic modeling; state space representation; solar cell, components sizing; design; simulation

1. INTRODUCTION

The use of DC/DC converters is essential in hybrid vehicles. Mainly, there exist two types of DC/DC converters onboard of a Hybrid Electric Vehicle (HEV). The first is a low power bidirectional DC/DC converter which connects the high voltage dc-link with a low voltage battery used to supply low power loads. The second is a high power bidirectional DC/DC converter used to connect the main energy storage unit with the electric traction drive system [1]. This paper presents modeling, design and analysis of the later converter. A Hybrid Energy Storage System (HESS) composed of a battery unit and an Ultra Capacitor (UC) pack is considered. Based on the study done in [2], a parallel dc-linked multi-input converter with half-bridge bidirectional DC/DC cells is chosen to link the battery/UC storage unit with the dc-link. The DC/DC converter is used to provide a regulated dc voltage at higher level to the inverter and to control power flow to and from the electric drive during motoring and generating modes respectively. The paper mainly focuses on modeling the proposed converter for both dynamic and steady state analysis.

2. ELECTRIC TRACTION SYSTEM SPECIFICATIONS

When designing a bidirectional DC/DC converter suitable for Power Electronic Interface (PEI) between the Energy Storage System (ESS) and the electric traction drive, it is important to indicate the specifications of the electric traction system. These specifications include identifying the level of hybridization of the vehicle; as well as the choice of hybrid drive train configuration, HESS, electric AC drive system, and DC/DC PEI configuration.

A. Level of Hybridization

In order to determine the dc-link voltage and the energy storage unit capacity at the DC/DC converter terminals, it is empirical to specify the vehicle hybridization level. A full HEV is chosen with large traction motor, high-capacity energy storage pack and main DC bus voltage around 200-300V.

B. Choice of Hybrid Drivetrain Configuration

A parallel hybrid drive train rather than a series one is chosen for several reasons. As shown in Fig.1, the vehicle can be driven by the ICE alone, the EM alone or both engines at the same time utilizing the best performance of each. Unlike series hybrids, parallel hybrids require less number of energy conversion stages and feature less power demands on the electrical system which makes parallel hybrids less expensive and more energy efficient.

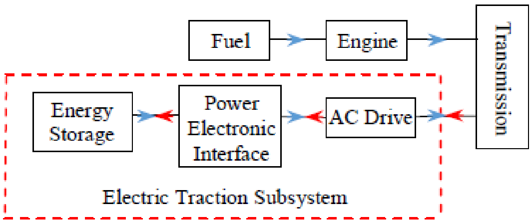

Fig. 1. Parallel hybrid drivetrain configuration

C. Choice of Electric AC Drive System

The AC drive is a classic Permanent Magnet Synchronous Motor (PMSM) drive which consists of a PMSM, a three-phase bridge voltage source inverter and a power electronic controller. Voltage source inverters are commonly used in HEV applications, where the source delivers a stiff voltage PMSMs exhibit higher efficiency, higher power density and high torque-to-inertia ratio when compared to induction motors. These advantages as well as the fast torque response make PMSMs good candidate for use in HEVs. The main disadvantage is the use of permanent magnets which are not only expensive but also sensitive to load and temperature.

3. DC-DC CONVERTER WITH HYBRID ENERGY STORAGE SYSTEM

A. Choice of Hybrid Energy Storage System

HEVs rely on the capability of their ESSs not only to store large amounts of energy but also to discharge according to load demand. A high power, high energy, and high efficiency ESS can be obtained by utilizing a hybrid battery /UC combination. The UC will increase the ESS power handling capability and reserve the amount of regenerative energy dissipated in the friction brakes due to the low power handling capability of the battery. The UC is used during transient pea k power demands and to capture regenerative energy which greatly reduces the voltage variations and stresses across the battery terminals and releases the burden of power converter interfacing the battery.

B. Choice of Power Electronics Interface Configuration

To get full control over the power flowing to and from the battery and to limit the fluctuating voltage levels at the UC terminals, it is necessary to utilize a DC/DC PEI between the storage units and the AC drive. The choice of a power converter as simple yet as efficient as possible to interface the HESS is discussed in [2]. Accordingly, a parallel dc-linked multi-input bidirectional converter is chosen as shown in Fig. 2. The proposed multi-input bidirectional DC/DC converter interfacing the battery/UC HESS and the traction drive in the HEV consists of two bidirectional half-bridge cells as shown in Fig. 3. Each half-bridge cell consists of an energy storage element (inductor), two IGBT power transistors, and two diodes for bidirectional current flow. IGBT s are chosen since they are suitable for low frequency, high power applications such as the full hybrid vehicle considered. An input capacitor interfacing the source acts as a filter limiting the source current ripple and the circulation of high-frequency components through the sources. This filtering is mainly used due to the Equivalent Series Resistance (ESR) of each of the battery and UC pack. Finally, one common output capacitor is shared between the two cells to minimize the voltage ripple at the DC bus and the inverter input terminals while t he battery and UC voltages remain at a level lower than that of the dc-link.

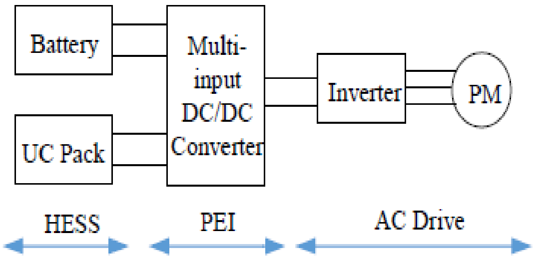

Fig. 2. Electric drive subsystem

4. DC-DC CONVERTER WITH SOLAR INPUT

A. PV array Characteristics

The use of single diode equivalent electric circuit makes it possible to model the characteristics of a PV cell. The mathematical model of a photovoltaic cell can be developed using MATLAB simulink toolbox. The basic equation from the theory of semiconductors that mathematically describes the I-V characteristic of the Ideal photovoltaic cell is given by

$$I = I_{pvcell}-I_d \qquad (1)$$

Where,

$$I_d = I_{0cell}[\exp(qv/\alpha kT)-1] \qquad (2)$$

Therefore

$$I = I_{pvcell}- I_{0cell}[\exp(qv/\alpha kT)-1] \qquad (3)$$

Where, 'I_{PVCell}' is the current generated by the incident light (it is directly proportional to the Sun irradiation), I_d is the diode equation, Io, cell' is the reverse saturation or leakage current of the diode, 'q' is the electron charge [1.60217646* 10−19C], k is the Boltzmann constant [1.3806503 *10−23J/K], 'T' is the temperature of the *p-n* junction, and 'a' is the diode ideality constant. Fig.3 shows the equivalent circuit of ideal PV cell.

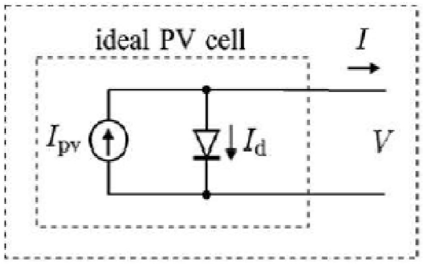

Fig.3 Equivalent circuit of ideal PV cell

Practical arrays are composed of several connected PV cells and the observation of the characteristics at the terminals of the PV array requires the inclusion of additional parameters (as shown in Fig.8) to the basic equation:

$$I = I_{pv}-I_o[\exp(V+IR_s/V_t\alpha)-1]-(V+IR_s/R_p) \qquad (4)$$

Where Vt = NskT/q is the thermal voltage of the array with 'Ns' cells are connected in series. Cells connected in parallel increases the current and cells connected in series provide greater output voltages. *V* and *I* are the terminal voltage and current. The equivalent circuit of ideal PV cell with the series resistance (Rs) and parallel resistance (Rp) is shown in Fig.4.

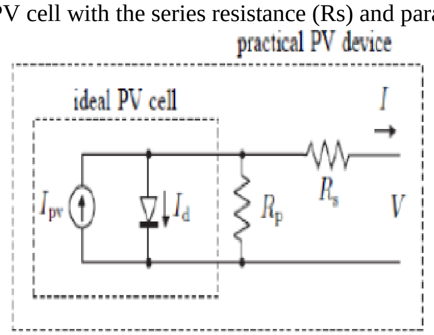

Fig.4 Equivalent circuit of ideal PV cell with Rp and Rs.

For a good solar cell, the series resistance (Rs), should be very small and the shunt (parallel) resistance (Rp), should be very large. For commercial solar cells (Rp) is much greater than the forward resistance of a diode. The I-V curve is shown in Fig.5. The curve has three important parameters namely open circuit voltage (Voc), short circuit current (Isc) and maximum power point (MPP). In this model single diode equivalent circuit is considered. The I-V characteristic of the photovoltaic device depends on the internal characteristics of the device and on external influences such as irradiation level and the temperature.

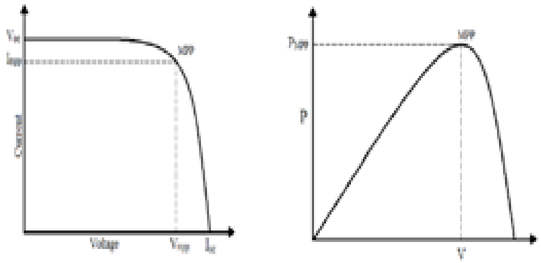

Fig.5 I-V and P-V characteristics of PV cell

5. DC-DC CONVERTER CIRCUIT AND OPERATION

Dynamic modeling of power converter is necessary in order to study its transient behavior and analyze how variations in the input voltage, load current, and duty cycle affect its output voltage [3]-[15]. However, a switching power converter is a nonlinear time-varying system which is difficult to analyze due to its intrinsic large signal nature. Small signal modeling is a commonly used approach to simplify the analysis, control and design of the converter nonlinear system by transforming it into a linear time-invariant system. This is usually done by taking the average value of the state variables over one switching period and is known as state space averaged modeling which enables analyzing the system dynamic behavior. The converter state space equations are used to derive the small signal averaged equations and the system transfer functions which are further used in the design of the controllers to regulate the system performance. Fig. 4 shows the switching power converter model. The converter state variables are the capacitors voltages, v_{Cin} and v_{Co}, and inductor current, i_L. The input variables are the load current, i_o, and the input source voltage, v_{in} for battery or UC. The output variable is the dc-link voltage, v_o, for UC fed converter and the source current, i_{in}, for battery fed converter.

The half-bridge converter i s bidirectional in current; thus, it is analyzed once as a boost converter stepping up voltage from the battery/UC to the load side and then as a buck converter stepping down voltage from th e dc-link to the source. The half-bridge converter never operates in discontinuous conduction mode due to the fact that the power devices (T1 with D2 and T2 with D1) function in complementary modes and have bidirectional load and source. This fact reduces current peaks as well as stresses on passive and active components. Moreover, the half-bridge converter switches function pair-wise, meaning that when T1 is ON, T2 is OFF, and vice versa. If both transistors lead at the same time there is a SC and risk of destroying components. Th us, the converter always operate in continuous conduction mod e with only two switching states for each of the boost and buck operations as shown in Table I.

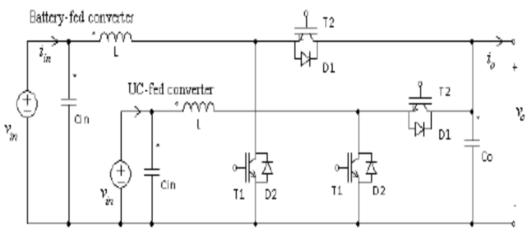

Fig .6 Parallel dc-linked multi-input bidirectional DC/DC converter

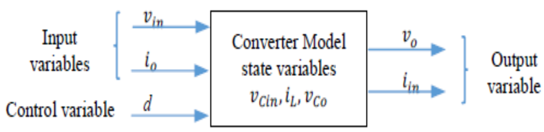

Fig .7 Power Switching Converter Model

Table1. Switching Configuration Of Half Bridge Converter

Switching State	T1	D1	T2	D2	Power Flow
Boost mode 1	ON	OFF	OFF	OFF	Source to Load
Boost mode 2	OFF	OFF	OFF	ON	Source to Load
Buck mode 1	OFF	OFF	ON	OFF	Load to Source
Buck mode 2	OFF	ON	OFF	OFF	Load to Source

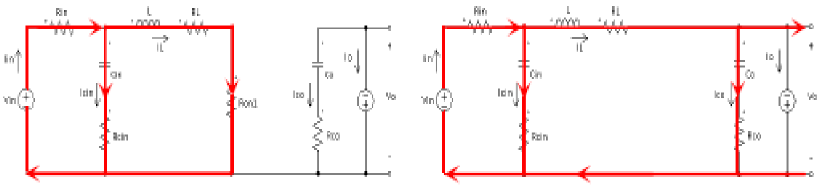

Fig. 8. Boost converter normal operation modes

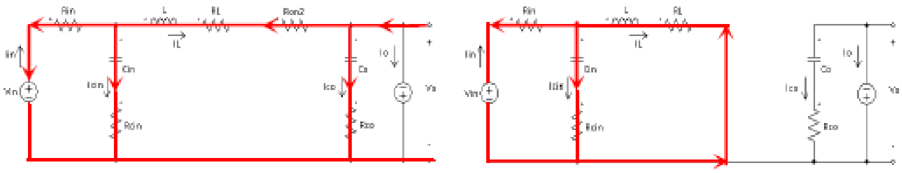

Fig. 9. Buck converter normal operation modes

6. SIMULATION RESULTS

The simulation circuits of both systems and corresponding results are shown in the following figures.

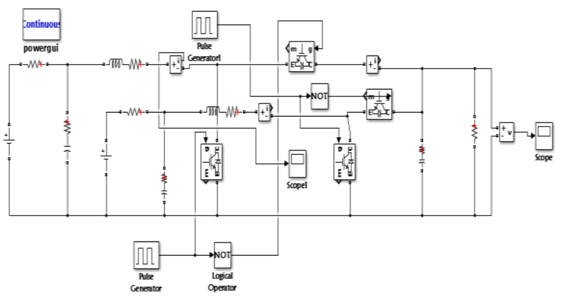

Fig .10 Simulation of DC-DC Converter with Battery/UC Input

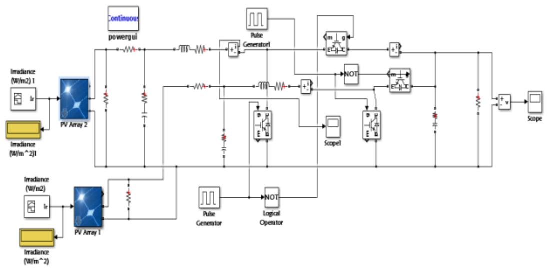

Fig .11 Simulation of DC-DC Converter with Solar Input

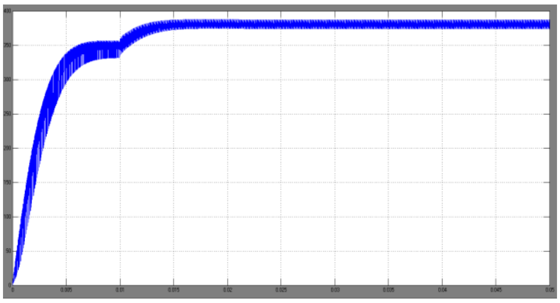

Fig .12 Output Voltage of DC-DC Converter with Battery/UC Input (200V i/p)

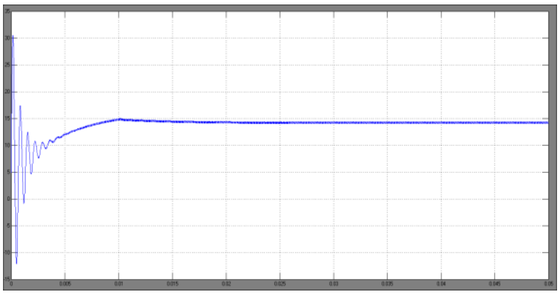

Fig .13 Solar Cell Input Voltage (15V)

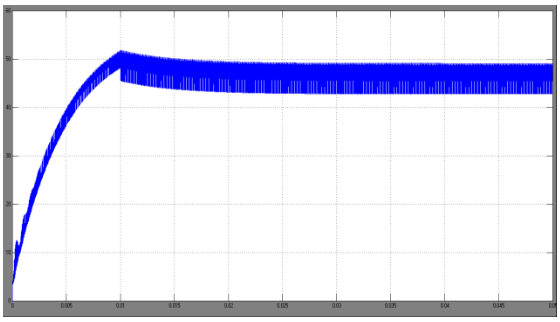

Figure .14 Output Voltage of DC-DC Converter with Solar Input (50V o/p)

7. CONCLUSION

This paper presents design and analysis of a half bridge bidirectional DC/DC converter as a PEI between a HESS and the main DC bus in HEVs. We considered two different inputs for the proposed DC-DC converter: 1. Hybrid Battery/UC pack 2. Solar input. The performance of the DC-DC converter is analyzed for both the inputs. It is observed that the converter working efficiently for the solar input too. The converter components are sized based on the design requirements of a full HEV. To verify the converter operation, the proposed design is simulated using Matlab/Simulink.

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Sandu Sridevi received B. Tech Degree in Electrical and Electronics Engineering from Sridevi Womens Engineering College(JNTUH) in the year of 2013. She is currently M. Tech student in the stream Power Electronic and Drives. Vignana Bharathi Institute of Technology, Hyderabad, India. And she is interested in the field of Power Electronics and Drives.
Email: sridevi14sri@gmail.com

P. Varaprasad Reddy is currently working as an Assistant Professor in Vignana Bharathi Institute of Technology, Hyderabad, India. His research areas include Power Electronic Drives and Renewable Energy Sources.
Email: varaprasad.vbit@gmail.com

