ANALYSIS AND CONTROL OF DOUBLE-INPUT INTEGRATED BUCK-BUCK-BOOST CONVERTER FOR HYBRID ELECTRIC VEHICLES

M.SubbaRao[1], Ch.Sai Babu[2], S.Satynarayana[3]

[1]Asst. Professor in Dept. of EEE, Vignan University, Vadlamudi, India.
[2]Professor in Dept. of EEE, College of Engineering JNTUK, Kakinada. India.
[3]Principal VRS& YRN Engg. College, Chirala, India.

ABSTRACT

The energy storage unit is one of the most important aspects in structure of hybrid electrical vehicles, since it directly impacts the performance, fuel economy, cost, and weight of the vehicle. In order to fully utilize the advantages of each energy storage device, employment of multi-input power converters is inevitable. In this paper analysis and control of double input integrated buck-buck-boost converter(DIIBBBC) is presented and operating modes are analyzed . In order to have simple control strategy as well as simpler compensator design a single loop control scheme, voltage-mode and current-limit control, are proposed here for the power distribution. Closed loop converter performance of this converter is simulated in MATLAB/Simulink and results show the performance of the converter.

KEYWORDS: *Integrated buck-buck-boost converter, Hybrid electrical vehicles, Multi-input power converters.*

I. INTRODUCTION

Ultracapacitors have been proposed to be utilized in the electrical distribution system of conventional and hybrid vehicles to serve applications like local energy cache, voltage smoothing, pseudo 42V architecture, and service life of batteries extension [1]. However, the high specific power of ultracapacitors is the major reason of them being used as intermediate energy storage unit during acceleration, hill climbing, and regenerative braking. An energy storage unit comprising both batteries and ultracapacitors have been choice for the future vehicles. The basic idea is to realize advantages of both batteries and ultra capacitors while keeping the weight of the entire energy storage unit minimized through an appropriate matching [2].

Several structures for combining batteries and ultracapacitors have been introduced in the literature [3]. However in these the power conversion efficiency is major challenge for the power supply designer. To meet these concerns multi-input converters with different topology combinations are coming up in the recent days [5]. Although there are several different types of switch-mode dc-dc converters (SMDC), belongs to buck, boost and buck-boost topologies, have been developed and reported in the literature to meet variety of application specific demands. but an integrated converter with buck and buck-boost feature is more suitable for this application. In view of this a double input integrated buck-buck-boost converter (DIIBBBC) and its control features are analyzed in this paper. In the following, Section 2 presents the operating modes of the DIIBBBC. In Section 3 the analysis of the DIIBBBC is expounded in state space model. Section 4 shows the Control Strategies for the DIIBBBC. Section 5 shows the MATLAB/simulation of DIIBBBC and the Simulation results. Finally, conclusions are provided in Section 6.

II. OPERATION OF THE DIIBBBC

The circuit diagram of proposed DIIBBBC, shown in Figure. 1. It consists of two input voltage sources $\boldsymbol{V_{HI}}$ and $\boldsymbol{V_{LO}}$, and an output voltage V_O .Power switches M_{HI} and M_{LO} are connected to the high voltage source $\boldsymbol{V_{HI}}$ and the low voltage source $\boldsymbol{V_{LO}}$, respectively. When the power switches are turned off, power diodes D_{HI} and D_{LO} will provide the by-pass path for the inductor current to flow continuously. By applying the PWM control scheme to the power switches M_{HI} and M_{LO}, the proposed double-input DCDC converter can draw power from two voltage sources individually or simultaneously or singly.

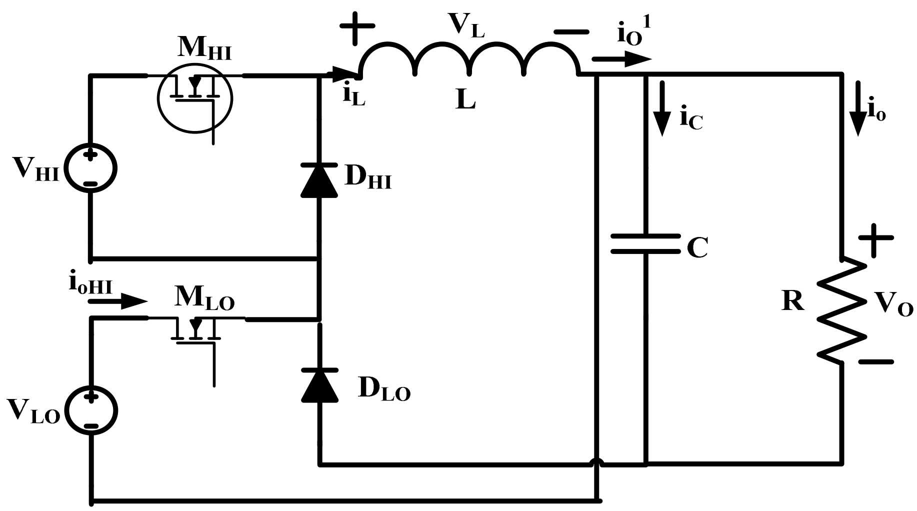


Figure 1. The proposed DIIBBBC

There are four different operation modes which can be explained as follows.

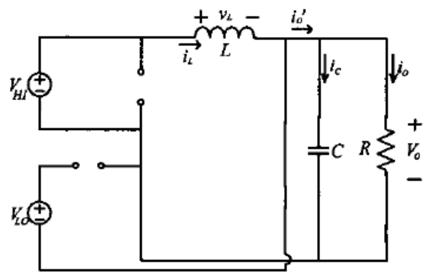
Mode I *(M_{HI} : on & M_{LO} :off)*
In Mode I, the power switch M_{HI} is turn on and M_{LO} is turn off. Because of the conduction of M_{HI}, power diode D_{HI} is reverse biased and can be treated as an open circuit. On the other hand, power switch M_{LO} for the low voltage source V_{LO} is turned off and the power diode D_{LO} will provide a by-pass path for inductor current i_L. The equivalent circuit of Mode I is shown in Figure 2(a). In this mode, the high voltage source will charge the energy storage components, inductor L and capacitor C, as well as provide the electric energy for the load.

Mode II *(M_{HI} : off & M_{LO} : on)*
In Mode II, the power switch M_{HI} is tumed off and M_{LO} is tumed on. Also, the power diode D_{HI} is turned on as a short circuit and D_{LO} is turned off as an open circuit. Figure.2(b) shows the equivalent circuit for Mode 11. During this operation mode, the low voltage source, V_{LO} will charge the inductor L, while the demanded load is provided by the output capacitor C.

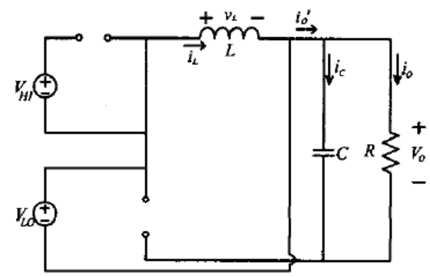
Mode III *(M_{HI} : off & M_{LO} :off)*
Both of the power switches M_{HI} and M_{LO} are turned off in Mode 111. Power diodes D_{HI} and D_{LO} will provide the current path for the inductor current. The equivalent circuit for Mode III is shown in Figure. 2(c). Both of the voltage sources V_{HI} and V_{LO} are disconnected from the proposed double-input converter. The electric energy stored in L and *C* will be released into the load.

Mode IV *(M_{HI} : on & M_{LO} :on)*
In Mode *IV,* both of M_{HI} and M_{LO} are turned on and D_{HI} and D_{LO} are turned off with reverse biased voltages. Two input voltage sources V_{HI} and V_{LO} are connected in series to charge the inductor. L. The demanded power for the load is now provided by the capacitor ***C.*** In this operation mode, both of the

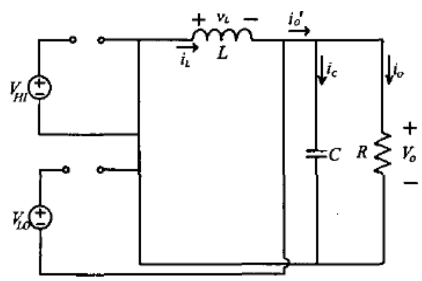
high now voltage sources will transfer electric energy into the proposed double-input DC-DC converter, simultaneously. The equivalent circuit for Mode IV is shown in Figure. 2(d).



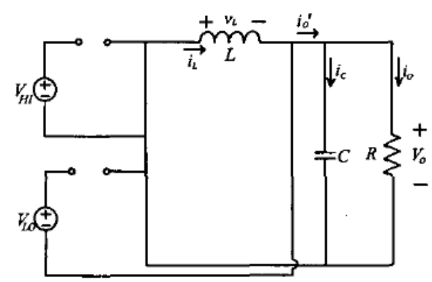
(a) Mode-I



(b) Mode-II



(c) Mode-III



(d) Mode-IV

Figure.2 operating modes of proposed DIIBBBC

Theoretically, the switching frequency of M_{HI} and M_{LO} can be different. However, in order to reduce the electromagnetic interference (EMI) and facilitate the filter design, M_{HI} and M_{LO} should he operated with the same switching frequency, practically .For the same switching frequency, M_{HI} and M_{LO} can be synchronized by the same turn-on transition with different turn-off moment, or the same turn-off transition with different turn-on moment. Although either way can achieve the synchronization of the switching control, only the latter one with turn-off synchronization will be introduced in this paper for further explanations. Figure.3. Shows the typical voltage and current waveforms for key components of the proposed DIIBBBC under turn-off synchronization.

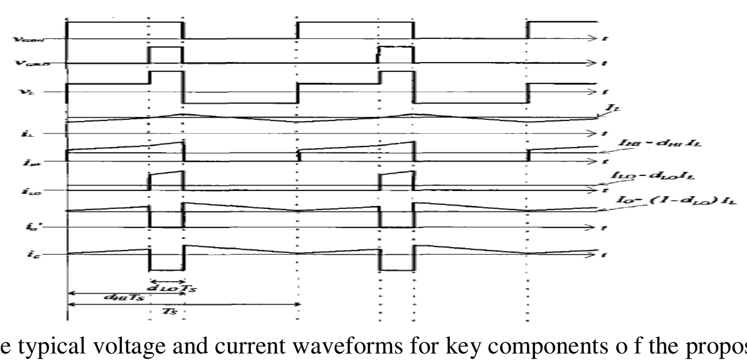


Figure 3. The typical voltage and current waveforms for key components o f the proposedDIIBBBC

III. STATE SPACE MODELLING OF DIIBBBC

In CICM the TIBBC goes through three topological stages in each switching period and it's power stage dynamics can be described by a set of state-space equations [10] given by:

$$x = A_K x = B_K u$$
$$v_0 = C_k x \qquad (1)$$

where $x = [\ i_L \quad v_c\ ]^T$ and $u = [v_g]$, k=1,2,3 and 4 for mode-1, mode-2, mode -3 and 4, respectively. Here the circuit operation depends on the type of controlling signal used for switching devices S_1 and S_2. In any case for proper functioning of the integrated converter, the gate control signals for the switching devices needs to be synchronized either in the form of trailing or leading-edge modulated pulses. Further, the operating modes depends on the duty ratio's of the switching devices, $d_1<d_2$ or d1> d2, and in any case only three modes will repeat in one switching cycle. Applying the state-space averaging analysis and upon simplification results the average model $\dot{x} = A\ x + B\ u$ where $A=(A_1d_1+A_2d_2+A_3d_3)$, $B=(B_1d_1+B_2d_2+B_3d_3)$ and these matrices are:

$$A_1 = \begin{bmatrix} -\frac{r_L}{L} - \frac{R}{(R+r_c)} & -\frac{R}{(R+r_c)} \\ \frac{R}{C(R+r_c)} & -\frac{1}{C(R+r_c)} \end{bmatrix}; B_1 = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & 0 \end{bmatrix} \tag{2}$$

$$A_2 = \begin{bmatrix} \frac{r_L}{L} & 0 \\ 0 & -\frac{1}{C(R+r_c)} \end{bmatrix}; B_2 = \begin{bmatrix} \frac{1}{L} & \frac{1}{L} \\ 0 & 0 \end{bmatrix} \tag{3}$$

$$A_3 = \begin{bmatrix} -\frac{r_L}{L} - \frac{r_c R}{(R+r_c)} & \frac{R}{(R+r_c)} \\ \frac{R}{C(R+r_c)} & \frac{1}{C(R+r_c)} \end{bmatrix}; B_3 = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & 0 \end{bmatrix} \tag{4}$$

$$A_4 = \begin{bmatrix} \frac{r_L}{L} & 0 \\ 0 & -\frac{1}{C(R+r_c)} \end{bmatrix}; B_4 = \begin{bmatrix} 0 & \frac{1}{L} \\ 0 & 0 \end{bmatrix} \tag{5}$$

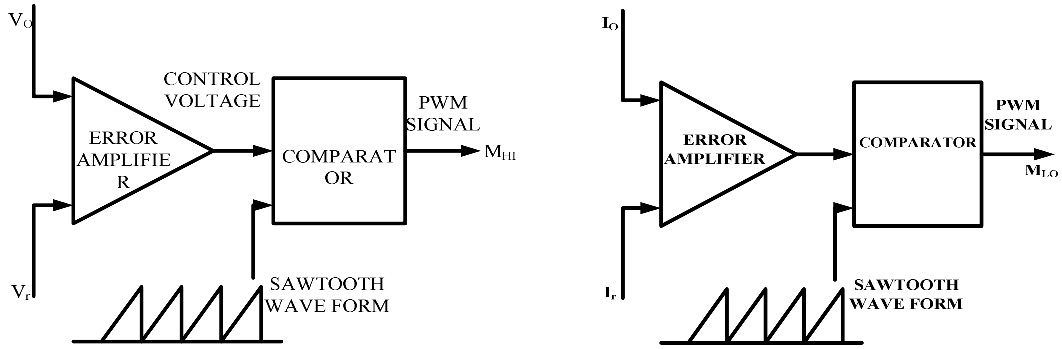
$$C_1 = C_3 = \begin{bmatrix} \frac{r_c R}{(R+r_c)} & \frac{R}{(R+r_c)} \end{bmatrix}; C_2 = C_4 \begin{bmatrix} 0 & \frac{R}{(R+r_c)} \end{bmatrix} \tag{6}$$

In this DIIBBBC the diodes will be the integral part of both buck and buck-boost converters, while the switching devices are unique to the individual converters. Load and it's filtering capacitor are common to both the converters. Buck converter is formed by: S1, D1, D2, L, R; while Buck-boost converter is formed by: S2, D1, D2, L, R. The steady-state load voltage can easily be established, either by employing volt-sec balance or through state-space model steady-state solution $[x] = A^{-1}BU$, as

$$V_o = \frac{d_2}{(1-d)_1} V_h + \frac{d_1}{(1-d_1)} V_l \tag{7}$$

IV. CONTROL STRATEGIES FOR THE DIIBBBC

In this paper for the DIIBBBC two inter dependent single-loop control schemes are proposed. This structure is capable of maintaining the load voltage regulation while ensuring the load distribution on the individual sources. The control schemes can be interchangeable from one to other depending on their power supplying capacity [10]. To illustrate the control principle, current control-loop for low voltage source (LVS), voltage control-loop for high voltage source (HVS) is shown in Figure. 4.



(a) Voltage Control (b) Current Control

Figure 4. Control of Multi-input Buck-Boost Converter.

V. SIMULATION AND RESULTS

To verify the developed modelling and controller design, a 200 W DIIBBBC system was designed to supply a constant dc bus/ load voltage of 48V from a two different dc sources: (i) high voltage power source: 60 V, (ii) low voltage power source: 30 V. The switching frequency of 50 kHz is used for driving both the switching devices. In order to conform the controller design analysis simulation studies has been carried out on The DIIBBBC. MATLAB/Simulink is used for this purpose. Figure 5 shows the Simulink model of proposed DIIBBBC system .The output voltage ,current and power waveforms are shown in figure 6,figure 7,figure 8,The Results of dynamic behaviour of the proposed converter is shown Figure 9, Figure 10and Figure 11.The output voltage which does not affect due to the step transient as shown in Figure 9.

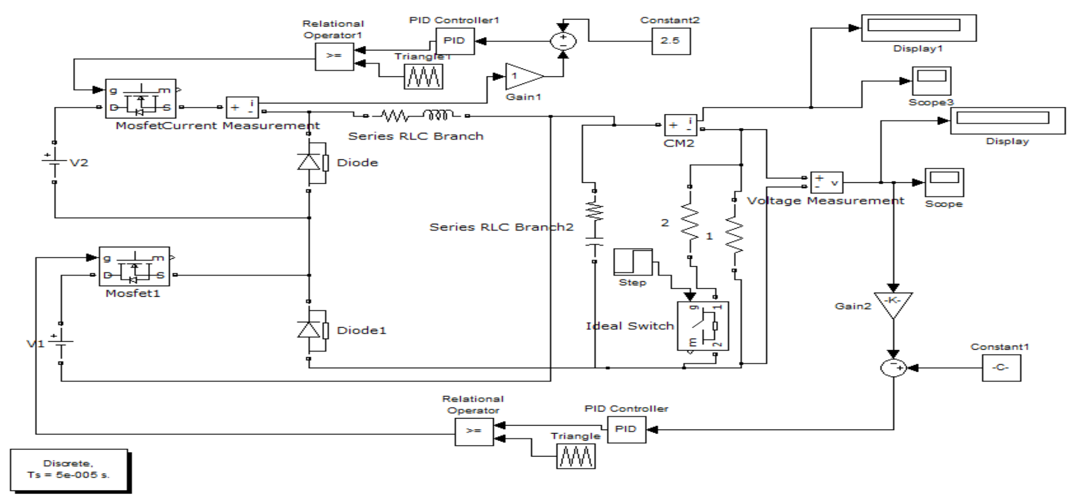


Figure 5.TheMATLAB/simulink model of proposed DIIBBBC

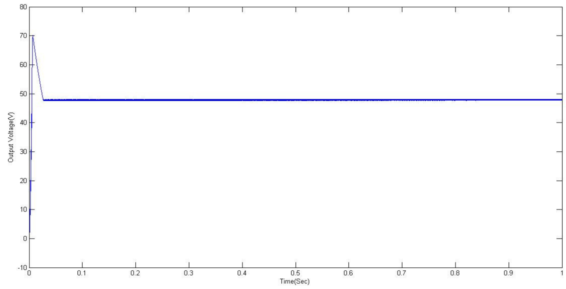


Figure 6. Output Voltage(V)

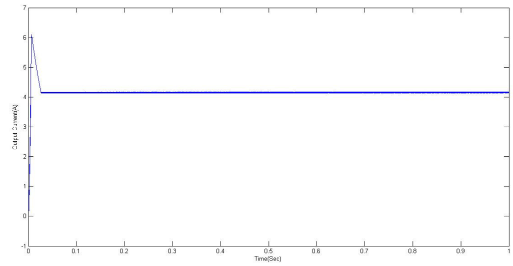


Figure 7. Output Current(A)

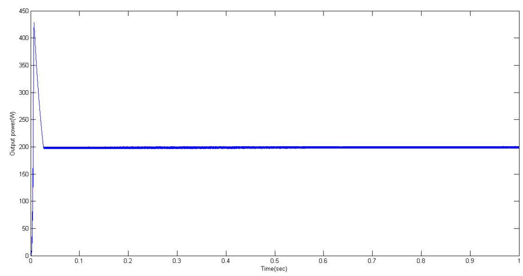


Figure 8. Output power(W)

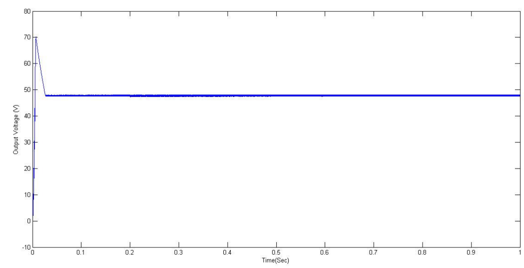


Figure 9. Output Voltage(V) with step change

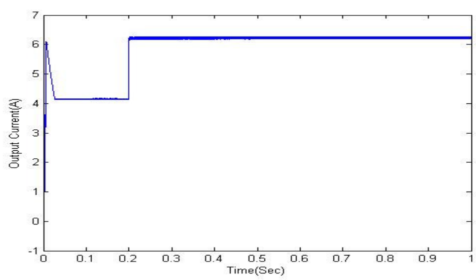


Figure 10. Output Current(A) with step change

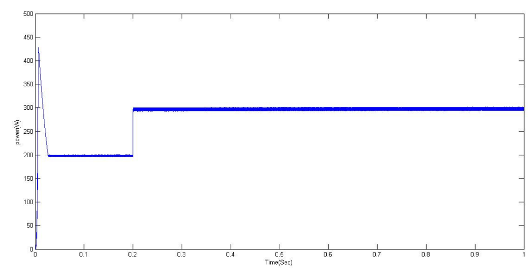


Figure 11. Output Power(W) with step change

VI. CONCLUSION

Double input integrated buck-buck-boost converter (DIIBBBC) is presented and operating principle including operating modes, the steady state analysis and power flow control is analyzed. Validity of single-loop control strategies, voltage mode and current-mode, have been tested for load voltage regulation and power distribution. The closed-loop converter design was verified using MATLAB simulink and results proves the performance of the converter. Also, the step-load change response shows that the expected power management capability can be achieved.

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Biographies:

SubbaRao. M received B.Tech from JNTUH in 2000,M.Tech from JNTUA in 2007. He is currently pursuing the Ph.D. Degree at JNTU college of Engineering, Kakinada. His research interests include Power Electronics and Drives.

Sai Babu. Ch obtained Ph.D Degree in Reliability Studies of HVDC Converters from JNTU, Hyderabad. Currently he is working as a Professor in Dept. of EEE in University College of Engineering, JNT University, Kakinada. His areas of interest are Power Electronics and Drives, Power System Reliability, HVDC Converter.

Satyanarayana.S, obtained Ph.D. Degree in Distribution Automation from JNTU college of Engineering, Hyderabad .currently he is working as a principal VRS& YRN Engg. College, Chirala. His research interests include Distribution Automation and Power Systems.