Modelling and Control of Bidirectional Buck-Boost Converter for Electric Vehicles Applications

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***Abstract*— The present paper study modelling, design consideration and control of a bidirectional DC/DC buck-boost converter for application in hybrid and electric vehicles. The proposed model includes electric motor, dynamics of the vehicle and theirs control. A mathematical model of the DC/DC buck-boost converter is described with differential equations during the both the boost and buck regions of operation. The control system is created and realized with proportional-integral regulator. The proposed solution is realized in visual environment MATLAB/Simulink. The obtained results demonstrates that the proposed solution is suitable for different electric vehicles applications.**

Keywords*— Bidirectional DC/DC converters, Control, Electric and hybrid vehicles, Modelling.

I. INTRODUCTION

Recently, the usage of the electric vehicle (EVs) in the modern society is significantly growing. The electric motor, being able to operate both as a motor during acceleration and generator during braking allows for a more controlled energy conversion in the vehicle. To realize the possibility of fully controlling the energy in both directions the onboard DC/DC converter must be able to accept both of its ports as potential energy sources. These converters are called bi-directional DC/DC converters and their control and analysis are very important in order to fully utilize the advantages of full electric propulsion. These converters can operates with fixed switching frequency and variable duty cycle, which allows several working modes such as step down function(buck), step-up function(boost) and the both (buck-boost) [1-3, 4, 5, 6]. These characteristics allows a process of energy storage.

II. MATHEMATICAL MODEL

On Figure 1 a schematic of a typical drive system for an EV is presented. It consists of an electric battery as an energy storage element and, respectively, an energy source, a bidirectional buck-boost DC/DC converter, inverter and permanent magnet synchronous machine. The DC/DC converter and its modes of operation is the main focus of this manuscript.

The system is described during the whole commutation period. When the converter operation in boost mode the following equations can be obtained for the state variables (1-4) [8, 9, 10]:

$$\frac{d}{dt}i_{L1}(t) = \frac{1}{L_1}(v(t) - R_{L1}i_{L1}(t) - v_{C1}(t).(1 - d(t))) \quad (1)$$

$$\frac{d}{dt}i_{L2}(t) = \frac{1}{L_2}(v_{C1}(t) - R_{L2}i_{L2}(t) - v_{C2}(t)) \quad (2)$$

$$\frac{d}{dt}v_{C1}(t) = \frac{1}{C_1}(i_{L1}(t).(1 - d(t)) - i_{L2}(t)) \quad (3)$$

$$\frac{d}{dt}v_{C2}(t) = \frac{1}{C_2}\left(i_{L2}(t) - \frac{v_{C2}(t)}{R} - I_{load}\right) \quad (4)$$

When operating in buck mode the equations for the state variables are (5-8).

$$\frac{d}{dt}i_{L1}(t) = \frac{1}{L_1}(v(t) - R_{L1}i_{L1}(t) - v_{C1}(t).(1 - d(t))) \quad (5)$$

$$\frac{d}{dt}i_{L2}(t) = \frac{1}{L_2}(v_{C1}(t) - R_{L2}i_{L2}(t) - v_{C2}(t)) \quad (6)$$

$$\frac{d}{dt}v_{C1}(t) = \frac{1}{C_1}(i_{L1}(t).(1 - d(t)) - i_{L2}(t)) \quad (7)$$

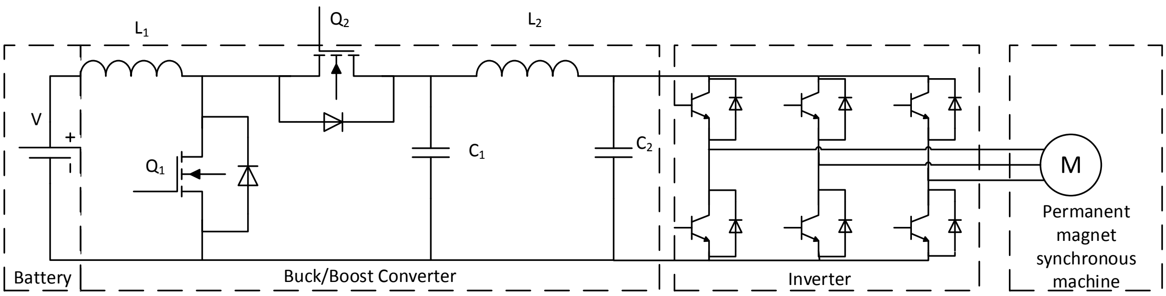

Fig. 1. Investigated topology of a pure electric propulsion vehicle

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$$\frac{d}{dt}v_{C2}(t)=\frac{1}{C_2}\left(i_{L2}(t)-\frac{v_{C2}(t)}{R}+I_{load}\right) \quad (8)$$

Where v is the voltage of the source, v_{C1} and v_{C2} are the voltage of the capacitors, $d(t)$ is the duty cycle, i_{L1} and i_{L2} are the currents, R_{L1} and R_{L2} are parasitic resistance of the inductors L_1 and L_2.

$$L_2=\frac{1}{8}\frac{\Delta v_{C1}T}{\Delta i_{L2}} \quad (14)$$

The current through the inductor L_2 is:

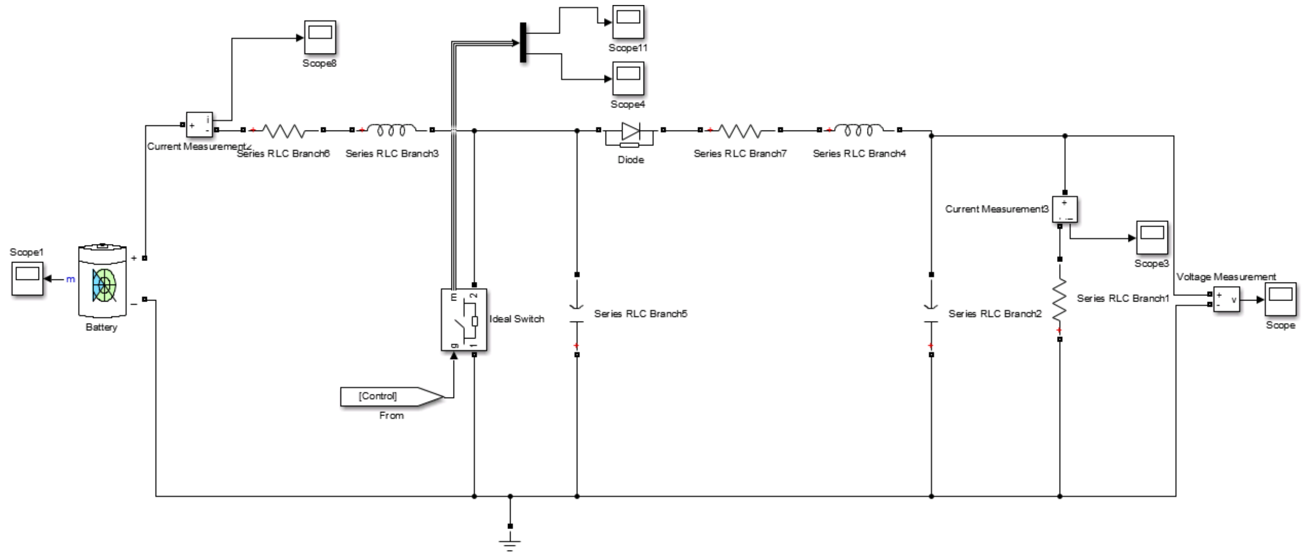

Fig. 2. Schematic of the proposed model realized in MATLAB/Simulink

A. Design of the passive components

With the following equations from (9) to (22) are designed the passive elements in the bidirectional converter. First of all, the ripple criterion is assigned for the current ripple in inductor L_1 and his value is obtained. After that the value of inductor L_2 is approximately one tenth from the value of inductor L_1 [11, 12]. The design of the two capacitors are also presented in [12]. The current ripple Δi_{L1} are described with the following equation:

$$\Delta i_{L1}=\frac{1}{2}\frac{v}{L_1}dT \quad (9)$$

And the value of the inductor L_1 is expressed as:

$$L_1=\frac{1}{2}\frac{v}{\Delta i_{L1}}dT \quad (10)$$

The value of the capacitor C_1 is obtained by the voltage ripple with the following equation:

$$C_1=\frac{1}{2}\frac{i_{L2}}{\Delta v_{C1}}dT \quad (11)$$

For design of the other components is used the switching ripple. With the equation (12) is defined total flux linkage.

$$\lambda_{L2}=L_2\left(2\Delta i_{L2}\right) \quad (12)$$

Which also can be expresses as:

$$\lambda_{L2}=\int_{\frac{1}{2}dT}^{dT+\frac{1}{2}(1-d)T} vL_2(t)dT=\frac{1}{4}T\Delta v_{C1} \quad (13)$$

After calculation of (12) and (13), it can be obtained the value of inductor L_2:

$$i_{L2}(t)=\frac{1}{L_2}\int v_{L2}(t)dt \quad (15)$$

The total charge of the capacitor C_2 can be calculated as its follow:

$$q_{C2}=\int_0^{dT}\frac{-i_{L2}}{2C_1L_2}t^2dt=\frac{1}{8}\frac{i_{L2}d^3T^3}{C_1L_2} \quad (16)$$

and it is defined by:

$$q_{C2}=C_2\left(2\Delta v_{C2}\right) \quad (17)$$

From the presented equations the value of the capacitor C_2 is obtained:

$$C_2=\frac{1}{16}\frac{i_{L2}d^3T^3}{C_1L_2\Delta v_{C2}} \quad (18)$$

Considering this calculation the values of the passive components are:

$$L_1=\frac{1}{2}\frac{200V}{1.3125A}\left(1-\frac{200V}{350V}\right)\frac{1}{40KHz}\cong 816\mu H \quad (19)$$

$$L_2=\frac{L_1}{10}=81.6\mu H \quad (20)$$

After consideration of the ratio between the two capacitors the value of the C_2 can be expressed as [13, 14]:

$$C_2=\frac{5}{16}\frac{i_{L2}d^3T^3}{C_1L_2\Delta v_{C2}} \quad (21)$$

The damping resistance used in this model is [15, 16]:

$$0 < R_d < \frac{V_{C2}^2}{P_{\max}} = \frac{(350V)^2}{1.5kW} = 81.67\Omega \tag{22}$$

In Table 1 and 2 are presented the calculated parameters from the realized model of the power electronic device.

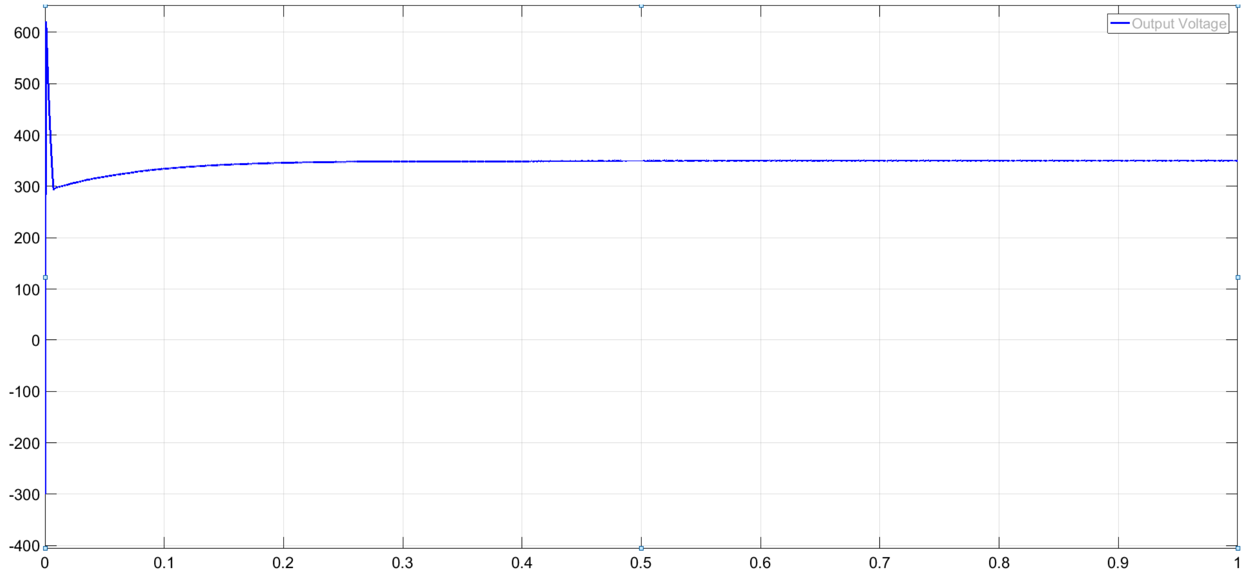

Fig. 3. Output Voltage

TABLE I. DESIGN PARAMETERS

Parameters	**Designation**	**Values**
Input Voltage	V	200[V]
Output Voltage	V_{C2}	350[V]
Nominal power	P_n	1.5kW
Switching frequency	f_s	40kHz
Input current ripple	$\Delta i_{L,\%}$	17.5%
Input current ripple	Δi_L	1.3125 [A]
Output voltage ripple	$\Delta v_{L,\%}$	0.5%
Ratio of the inductors	L_1/L_2	10
Ratio of the capacitors	C_2/C_1	5

TABLE II. DESIGN PARAMETERS

Parameters	**Designation**	**Values**
Inductor	L_1	816[μH]
Inductor	L_2	81.6[μH]
Capacitor	C_1	1[μF]
Capacitor	C_2	10[μF]
Damping resistance	R_d	82Ω

B. *Modeling of the converter controller*

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In Fig. 4 shows the block diagram of the synthesized and implemented energy flow management system in the electric vehicle in question. The model of this system is implemented in the visual programming environment. From the graphical results shown, the regulator is well tuned and stabilizes the output voltage of the power electronic device. In this case, a proportional-integral (PI) regulator is used, making it a relatively simple and standard solution for power electronics control system. More advanced solutions such as: neural networks, slide-mode control, predictive control and more are used for more accurate control.

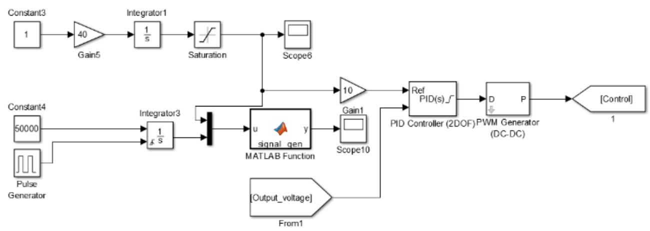

Fig.4. Block schematic of the controlerk

III. RESULTS OF THE NUMERICAL EXPERIMENTS

The simulation results are obtained in visual environment MATLAB/Simulink. Figure 3 shows the output voltage of the DC/DC converter. From this figure it can be concluded that the used data execute the reference value of 350V.

The model of a DC motor is realized with equivalent damping resistance. In Fig. 5 shows the output current of the DC-DC converter (the current through the inductor L_2). In both figures, the X axis indicates the simulation time in seconds.

IV. CONCLUSION

The paper shows a model of a bidirectional DC/DC buck-boost converter that can be used in an electric vehicle. The control system is realized with a PI regulator and simulational results are shown demonstrating its operation. The model

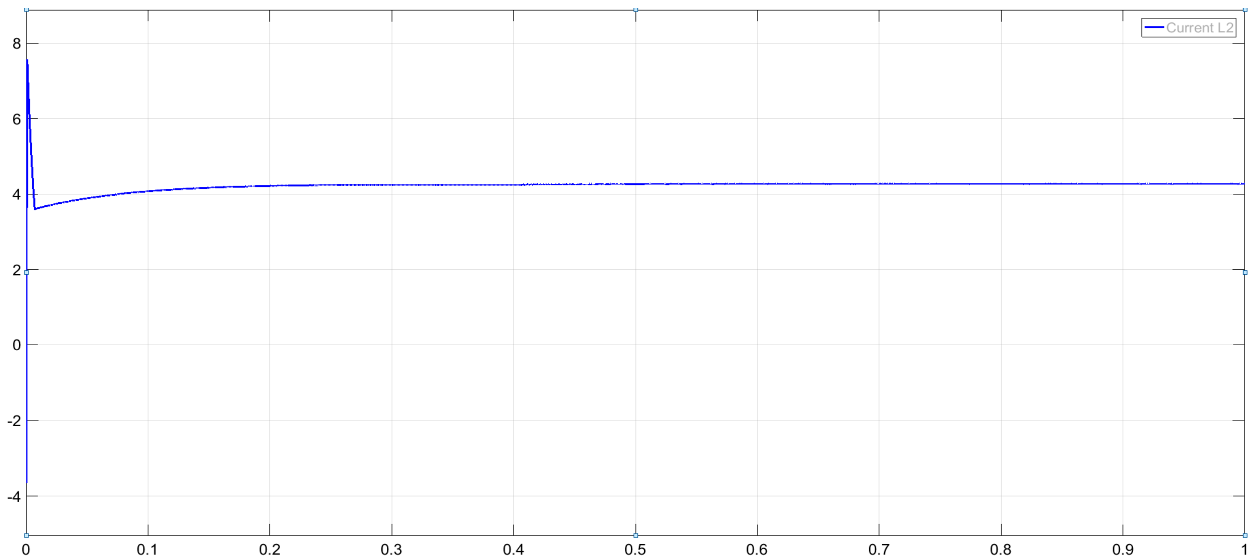

Fig.5. Current throught the inductor L_2

could be useful tool for testing of different operation modes such as acceleration and regenerative braking.

The results obtained make it possible to determine the limit (limit) values of currents and voltages in the power circuit. In this way, design restrictions are set, such as the topology type, the control frequency, and so on.

On the other hand, the presented model may be reduced using some of the known model reduction techniques. In this way, numerical experiments with large simulation times (of the order of minutes) are possible. This is important when complex objects with different time constants are modeled: the electronics, the electric motor and the mechanical part of the vehicle.

In further researches the proposed model could be significant contribution for examination of different driving cycles such as urban and suburban. The determination of the optimal control of energy flows could be considerably simple with the aid of this researches. Thus, this study could assist with the evaluation of the efficiency of the electric vehicle.

Acknowledgment

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