Fuzzy Logic Control Based Integrated 2D Buck-Boost Converter

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Abstract—*An integrated 2D buck–boost converter is developed by combining the KY converter and the synchronously rectified (SR) buck converter. The converter has positive output voltage different from negative output voltage of the traditional buck-boost converter. The converter operates in continuous conduction mode inherently and it possesses the non-pulsating output current, thereby not only decreasing the current stress on the output capacitor but also reducing the output voltage ripple. Both the KY converter and the SR buck converter uses the same power switches, thereby causing the required circuit to be compact and the corresponding cost to be down. During the magnetization period, the input voltage of the KY converter comes from the input voltage source, whereas during the demagnetization period, the input voltage of the KY converter comes from the output voltage of the SR buck converter. Simulation of the converter is carried out using MATLAB-SIMULINK software. Fuzzy logic control is used to control the integrated 2D buck-boost converter. Simulation and experimental results are presented to validate the proposed converter topology and control scheme.*

Keywords-*Buck-boost converter, KY converter, sinchronously rectified (SR) buck converter.*

I. INTRODUCTION

Many applications require voltage bucking or boosting converters, such as portable devices, car electronic devices, etc. This is because the battery has quite large variations in output voltage. So additional switching power supply is needed for processing the varied input voltage to generate the stabilized output voltage. There are several types of non-isolated voltage buck/boosting converter, such as buck–boost converter, single-ended primary inductor converter (SEPIC), Cuk converter, Zeta converter, Luo converter and its derivatives, etc. When these converters operating in the continuous conduction mode (CCM), possess low system stability. Consequently, a KY buck–boost converter has been developed to overcome the aforementioned problems. A KY buck-boost converter is a voltage bucking/boosting converter which has the output voltage up to double input voltage [10]. Fig. 1 shows a KY buck-boost converter. As compared with conventional buck-boost converter, this converter has ultra-fast transient responses, similar to the behaviour of the buck converter; this converter always operates in CCM, thereby causing the current stress on the output capacitor and the corresponding output ripple to be small [9-11]. But it has a serious problem in four power switches used, thereby causing the corresponding cost to be up [1].

In order to reduce the number of power switches in the KY buck-boost converter, the KY converter and the SR buck converter are combined into a buck–boost converter (i.e., integrated 2D buck-boost converter), both use the same power switches [1].

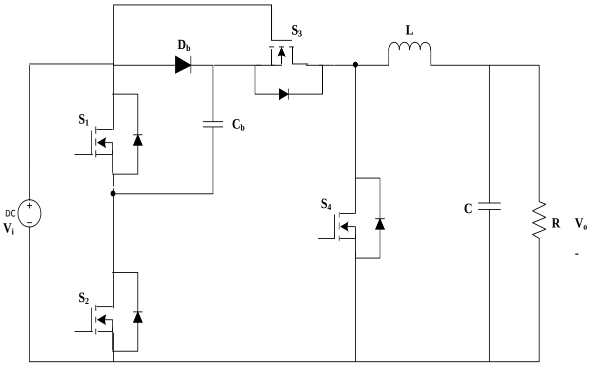


Fig.1. KY buck-boost converter

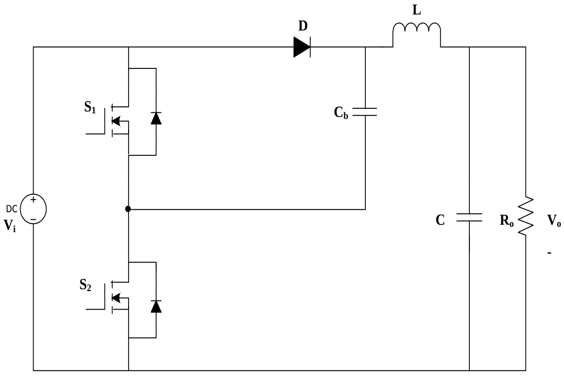


Fig. 2. KY converter.

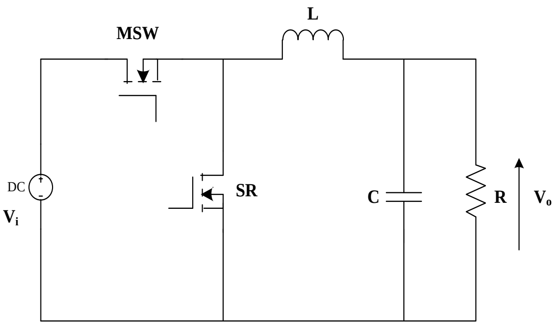


Fig. 3. SR buck converter.

Fig. 2 shows a KY converter which consists of two MOSFET switches S1 and S2 along with anti-diodes DI and D2 respectively, one diode D, one energy-transferring capacitor C_b which is large enough to keep the voltage across itself constant at the value of the input voltage, one output inductor L, and one output capacitor C. It is a voltage boosting converter. Unlike the traditional non-isolated boost converter, this converter possesses fast transient load responses, similar to the buck converter behavior. Besides, it possesses non-pulsating output current, thereby not only decreasing the current stress on the output capacitor but also reducing the output voltage ripples [3-8].

Fig.3 shows a synchronously rectified (SR) buck converter. The diode in a conventional buck converter is replaced by a MOSFET to form a synchronously rectified (SR) buck converter. Thereby the on-state resistance of diode can be avoided and the power loss can be limit. Synchronous rectification provides greater efficiency and density. Conduction loss on schottky diode can reduce by replacing the diode with MOSFET at little system cost impact [13].

The proposed converter always operates in CCM due to the positive and negative inductor currents existing at light load simultaneously. As compared with the converters previously stated, this converter has the non-pulsating output inductor current, thereby causing the current stress on the output capacitor to be decreased, and hence, the corresponding output voltage ripple to be small. Moreover, such a converter has the positive output voltage different from the negative output voltage of the traditional buck–boost converter.

The proposed converter is used to buck/boost voltage. The voltage boosting range is not so high, that is, the voltages across two energy-transferring capacitors C1 and C2 are both D times the input voltage, where D is the duty cycle of the gate driving signal for the main switch. The voltages across two energy-transferring capacitors C1a and C1b for the hybrid cuk converter, the hybrid Zeta converter, and the hybrid SEPIC converter are 1/(1−D), D/(1−D), and 1/(1−D) times the input voltage, respectively [2]. Therefore, these converters have higher voltage conversion ratios than that of the proposed converter. Therefore, from an industrial point of view, the above mentioned converters are suitable for sustainable energy applications, whereas the proposed converter is suitable for portable products.

II. INTEGRATED 2D BUCK-BOOST CONVERTER

Fig.4 shows an integrated 2D buck–boost converter, which combines two converters using the same power switches. One is the SR buck converter, which is built up by two power switches S_1 and S_2, one inductor L_1, one energy-transferring capacitor C_1, whereas the other is the KY converter, which is constructed by two power switches S_1 and S_2, one power diode D_1 which is disconnected from the input voltage source and connected to the output of the SR buck converter, one energy-transferring capacitor C_2, one output inductor L_2, and one output capacitor C_o. The output load is signified by R_o. During the magnetization period, the input voltage of the KY converter comes from the input voltage source and during the demagnetization period, the input voltage of the KY converter comes from the output voltage of the SR buck converter.

During the startup period with S_1 being ON and S_2 being OFF, L_1 and L_2 are both magnetized. At the same time, C_1 is charged, and the voltage across C_1 is positive, whereas C_2 is reverse charged, and the voltage across C_2 is negative. Sequentially, during the startup period with S_1 being OFF and S_2 being ON, L_1 and L_2 are both demagnetized. At the same time, C_1 is discharged. Since C_2 is connected in parallel with C_1, C_2 is reverse charged with the voltage across C_2 being from negative to positive, and finally, the voltage across C_2 is the same as the voltage across C_1.

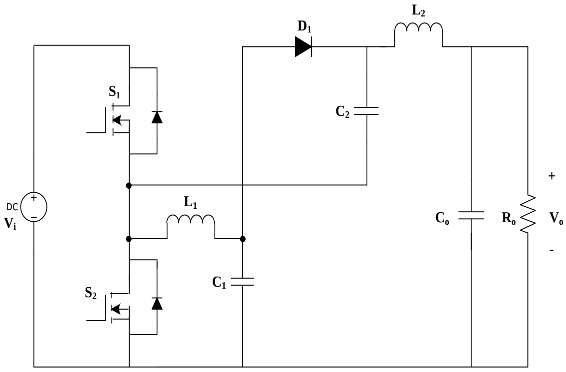


Fig. 4. Integrated 2D buck-boost converter.

There are some assumptions that are given as follows: 1) all the components are ideal; 2) the blanking times between S_1 and S_2 are omitted; 3) the voltage drops across the switches and diode during the turn-on period are negligible; 4) the values of C_1 and C_2 are large enough to keep $V_{C\,1}$ and $V_{C\,2}$ almost constant, that is, variations in $V_{C\,1}$ and $V_{C\,1}$ are quite small during the charging and discharging period;

and 5) the currents flowing through L_1 and L_2 are both positive. Since this converter always operates in CCM inherently, the turn-on type is (D, 1−D), where D is the duty cycle of the gate driving signal for S_1 and 1−D is the duty cycle of the gate driving signal for S_2.

The dc input voltage is signified by V_i, the dc output voltage is represented by V_o, the dc output current is expressed by I_o, the gate driving signals for S_1 and S_2 are indicated by M_1 and M_2, respectively, and the voltages on S_1 and S_2 are represented by v_{S1} and v_{S2}, respectively. The voltages on L_1 and L_2 are denoted by v_{L1} and v_{L2}, respectively, and the currents in L_1 and L_2 are signified by i_{L1} and i_{L2}, respectively, and the input current is expressed by i_i. Fig. 5 shows the key waveforms of the proposed converter with a switching period of T_s under i_{L1} and i_{L2} being positive for any time. It is noted that from Fig.5, the voltage stresses for S_1 and S_2 are both identical and equal to the input voltage, and the input current waveform is pulsating.

The converter will operate in two operating modes.

State 1: As shown in Fig. 5, S_1 is turned ON but S_2 is turned OFF. During this state, the input voltage provides energy for L_1 and C_1. Hence, the voltage across L_1 is V_i minus V_{C1}, thereby causing L_1 to be magnetized, and C_1 is charged. At the same time, the input voltage, together with C_2, provides the energy for L_2 and the output. Hence, the voltage across L_2 is V_i plus V_{C2} minus V_o, thereby causing L_2 to be magnetized, and C_2 is discharged.

$$v_{L1} = V_i - V_{C1} \qquad (1)$$

$$v_{L2} = V_i + V_{C2} - V_O \qquad (2)$$

State 2: As shown in Fig.6, S_1 is turned OFF but S_2 is turned ON. During this state, the energy stored in L_1 and C_1 is released to C_2 and the output via L_2. Hence, the voltage across L_1 is minus V_{C1}, thereby causing L_1 to be demagnetized, and C_1 is discharged. At the same time, the voltage across L_2 is V_{C2} minus V_o, thereby causing L_2 to be demagnetized, and C_2 is charged. Therefore, the associated equations are described as follows:

$$v_{L1} = -V_{C1} \qquad (3)$$

$$v_{L2} = V_{C2} - V_0 \qquad (4)$$

$$V_{C2} = V_{C1} \qquad (5)$$

By applying the voltage-second balance to (1) and (3), the following equation can be obtained as

$$(V_i - V_{C1})D\,T_S + (-V_{C1})(1-D)T_S = 0 \qquad (6)$$

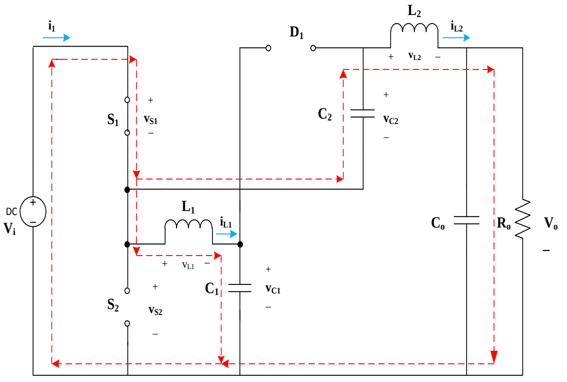


Fig. 5. Current flow in state 1.

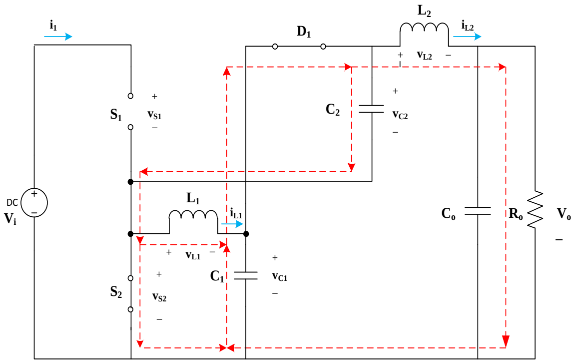


Fig. 6. Current flow in state 2.

Therefore, by simplifying (6), the following equation can be obtained as

$$V_{C1} = D\,V_i \qquad (7)$$

Sequentially, by applying the voltage-second balance to (2) and (4), the following equation can be obtained as

$$(V_i + V_{C2} - V_0)D\,T_S + (V_{C2} - V_O)(1-D)T_S = 0 \qquad (8)$$

Hence, by substituting (5) and (7) into (8), the voltage conversion ratio of the proposed converter can be obtained as

$$\frac{V_O}{V_i} = 2D \qquad (9)$$

Therefore, such a converter can operate in the buck mode as the duty cycle D is smaller than 0.5, whereas it can operate in the boost mode as D is larger than 0.5. In addition, based on (5), (7), and (9), the dc voltages across C1 and C2 can be expressed to be

$$V_{C1} = V_{C2} = 0.5\,V_O \qquad (10)$$

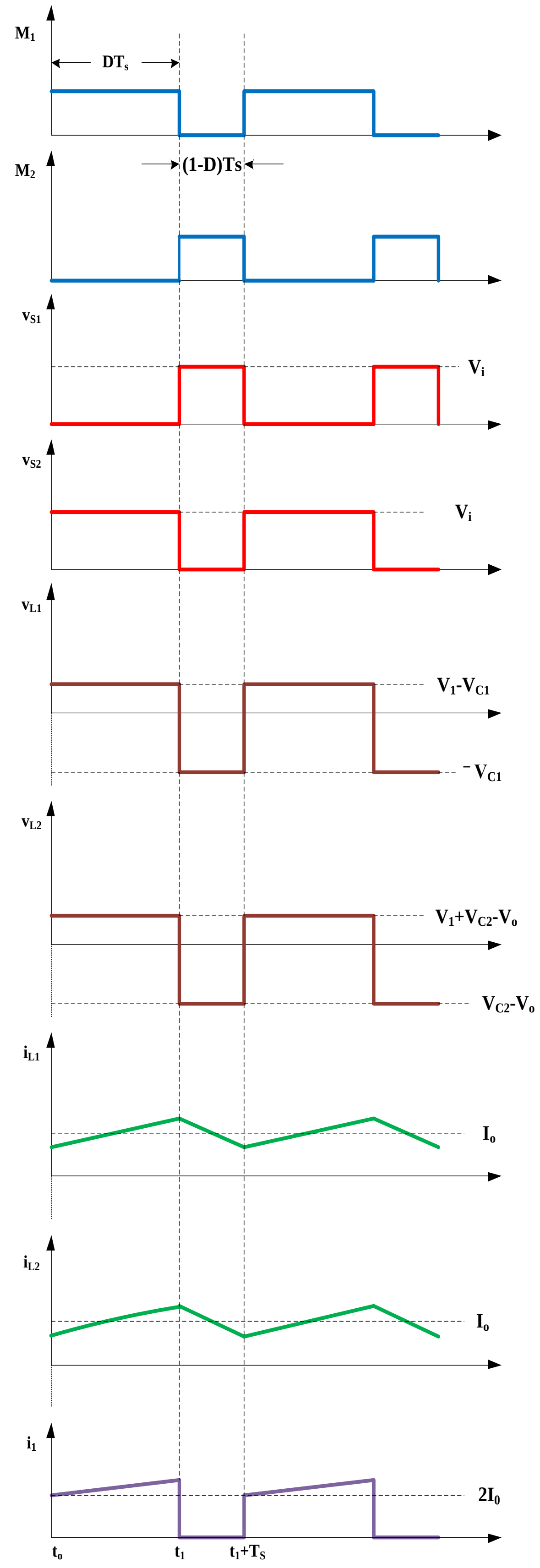


Fig. 7. Operating waveform of the integrated 2D buck-boost converter.

III. DESIGN EQUATIONS

Equation for the two inductors are given below.

$$L_1 \geq \frac{D_{min} \cdot (V_1 - V_{C1})}{\Delta i_{L1} \cdot f_s} \qquad (11)$$

$$L_2 \geq \frac{D_{min} \cdot (V_1 + V_{C2} - V_O)}{\Delta i_{L2} \cdot f_s} \qquad (12)$$

Equations for the energy transferring capacitors are

$$C_1 \geq \frac{I_{O-rated} \cdot D_{max}}{\Delta V_{C1} \cdot f_s} \qquad (13)$$

$$C_2 \geq \frac{I_{O-rated} \cdot D_{max}}{\Delta V_{C1} \cdot f_s} \qquad (14)$$

D_{max} is selected as 0.7 and D_{min} is 0.33.

IV. SIMULATION RESULT

Simulation the proposed integrated 2D buck-boost converter circuit is done in MATLAB R2014. The input voltage and the switching frequency are chosen as 5V and 30kHz respectively. The closed loop simulation of the converter is carried out using PI control and fuzzy logic control. Values for circuit components of the converter are presented in TABLE I. MOSFETs are used to realize the switches S_1 and S_2. The inductors L_1 and L_2 are selected as 15µH. The two energy transferring capacitors are selected as 470µF. The output capacitor and load resistance are selected as 470µF and 10Ω respectively.

Simulation of the circuit using PI control

Feedback control is provided to control the output voltage to the desired level. In a dc-dc converter with a given input voltage the average output voltage is controlled by adjusting the switch on and off durations. The control voltage is generally obtained by amplifying the error signal or difference between actual voltage and desired voltage. Any change in the input voltage is sensed as change in output voltage accordingly the error signal also changes. The error signal is used to change the duty ratio of the switching pulses to keep the voltage constant. The error signal is compared with repetitive waveform. This method is known as Pulse Width Modulation (PWM).

The sensed output voltage of the converter is compared with the reference voltage V_{ref}. The error signal is used by the PI controller to estimate the control voltage that is compared with a saw-tooth waveform in the pulse width modulator (PWM). The pulse signal produced by the PWM is fed to the two buffers that can be enabled by external signals. The comparators in the polarity detector unit enable the appropriate buffers to produce the gate pulses ($V_{g\,1}$ and $V_{g\,2}$) that control the MOSFETs of the boost and buck–boost converter during appropriate half cycles.

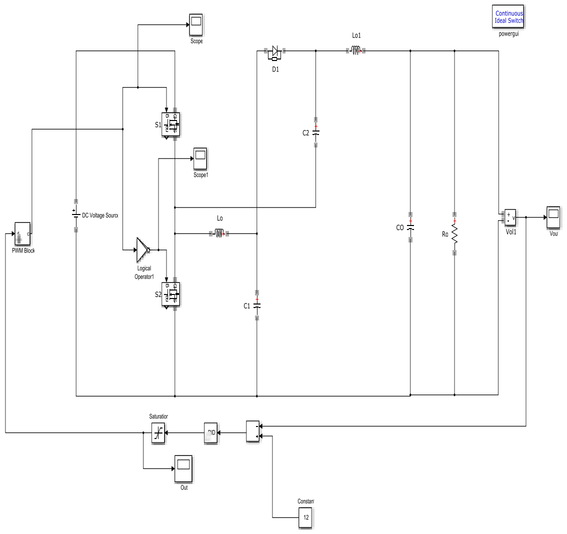
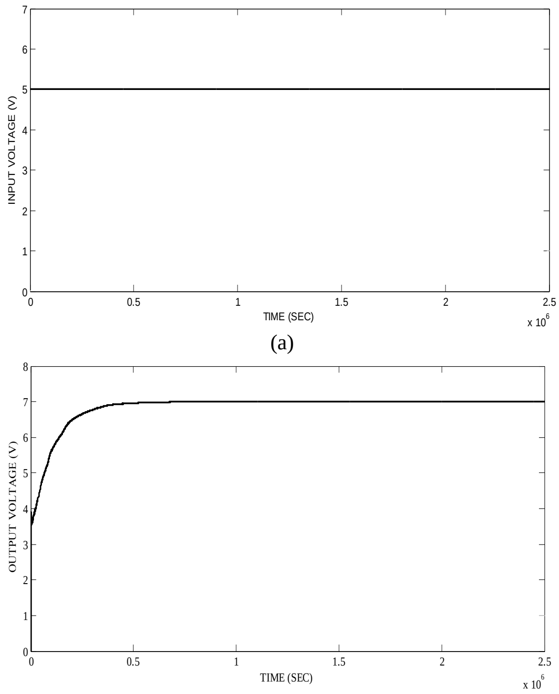


Fig. 8. Simulation circuit of the converter using PI control.



(a)

(b)

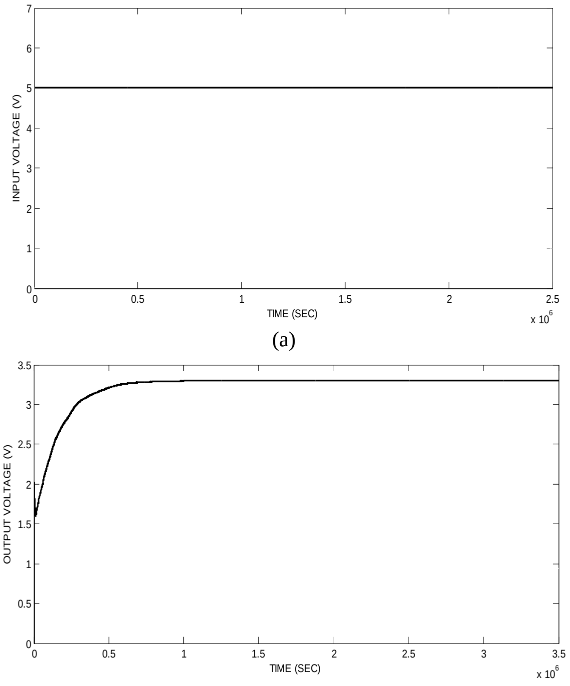
Fig. 9. (a) Input voltage and (b) Output voltage of converter during boost operation.

The input voltage given to the converter is 5V. During boost operation, output voltage of the converter is 7V and during the buck operation, output voltage of the converter is 3.3V. The input and output waveforms during boost and buck operations of the converter are shown in Fig. 9 and Fig. 10 respectively.

TABLE I

MAIN PARAMETERS OF THE SIMULATION

CIRCUIT COMPONENTS	VALUES
Input Voltage (DC)	5V
Inductors L_1, L_2	15μH
Capacitors C_1,C_2,C_O	470μF
Load resistance R_o	10Ω
Switching frequency	30KHz



(a)

(b)

Fig. 10 (a) Input voltage and (b) Output voltage of converter during buck operation.

Simulation of the circuit using fuzzy logic control

Fuzzy logic controller modeled for the integrated 2D buck-boost converter is shown in Fig. 11. The output voltage of the converter is compared with reference voltage by the comparator and the output of converter is error signal which is fed to the Fuzzy controller along with the change in error signal. The output of controller is duty cycle which is fed to PWM block and the PWM output is fed as switching signal to the converter as shown in Fig.11.

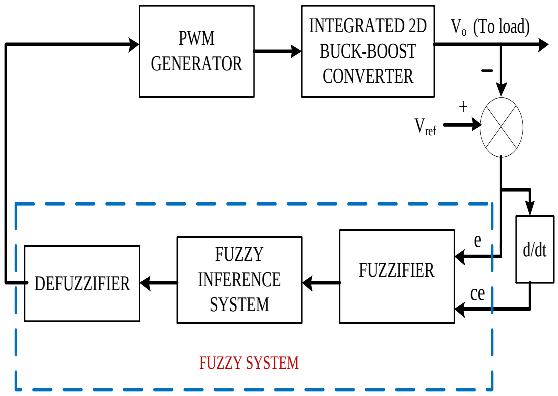


Fig. 11. Fuzzy logic control circuit.

Fuzzy logic control is used to control the output voltage of the integrated 2D buck-boost converter. Fuzzy logic controller mainly consists of three blocks as shown in Fig. 11. They are fuzzifier, fuzzy inference engine and defuzzifier. Input to the fuzzy logic controller is given to the fuzzifier block. The crisp input is converted in to fuzzy by using fuzzification method. After fuzzification the rule base is formed in the fuzzy inference engine. Based upon the rules the decision is made. Here, Mamdani's fuzzy inference method is used. Defuzzification is used to convert fuzzy value to the crisp value which is the output. Centroid defuzzification method is used here. The most important things in fuzzy logic control system designs are the process design of membership functions for inputs, outputs and the process design of fuzzy if-then rule knowledge base. They are very important in fuzzy logic control. For the DC drive, output voltage error (E) and change in output voltage error (d(E)/dt) are taken as the two input for the fuzzy controller.

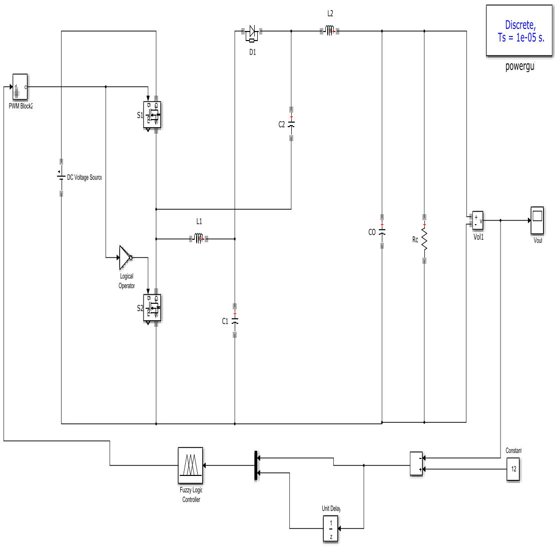
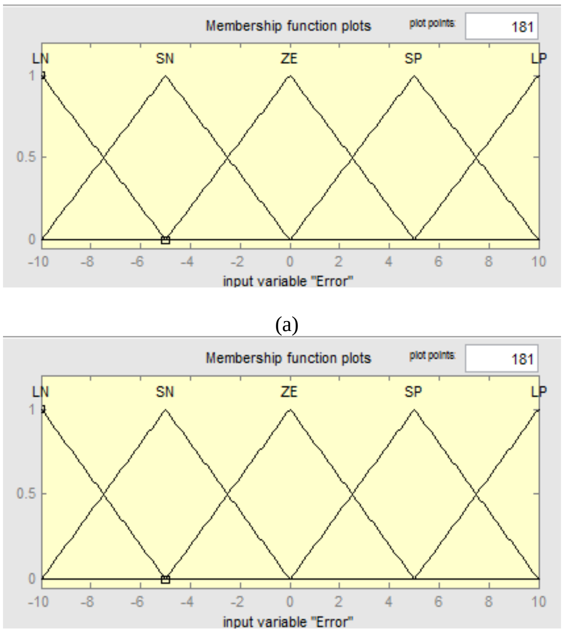


Fig. 12. Simulation model of integrated 2D buck-boost converter using fuzzy logic control.



(a)

(b)

Fig. 13. Input membership functions (a) Error and (b) Change in error.

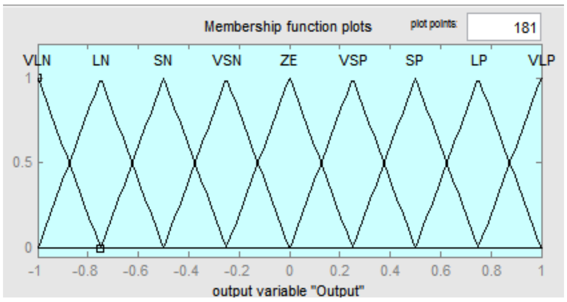


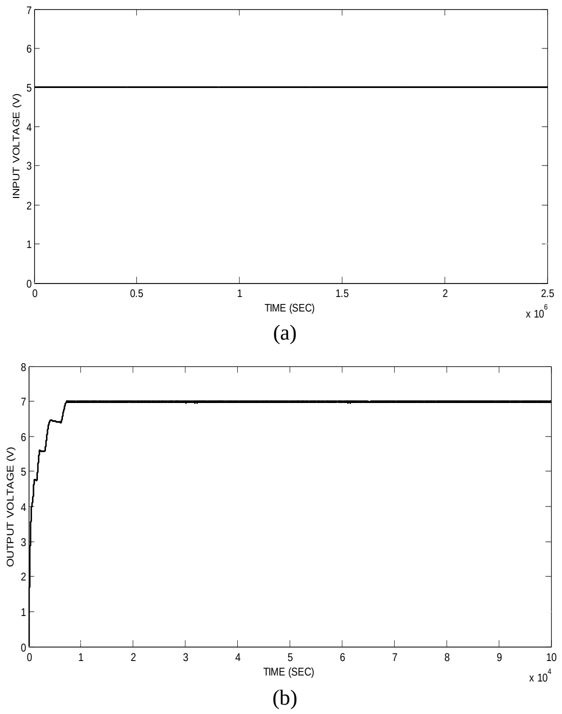
Fig. 14. Output membership function.

TABLE II

FUZZY RULE MATRIX.

E \ CE	LN	SN	ZE	SP	LP
LN	VLN	VLN	VLN	LN	ZE
SN	VLN	SN	VSN	ZE	LP
ZE	VLN	VSN	ZE	VSP	VLP
SP	LN	ZE	VSP	SP	VLP
LP	ZE	LP	VLP	SP	VLP

The input membership functions (error and change in error) and the output membership functions are shown in Fig. 13 and 14 respectively. The fuzzy rule matrix used in the simulation is shown in TABLE II.

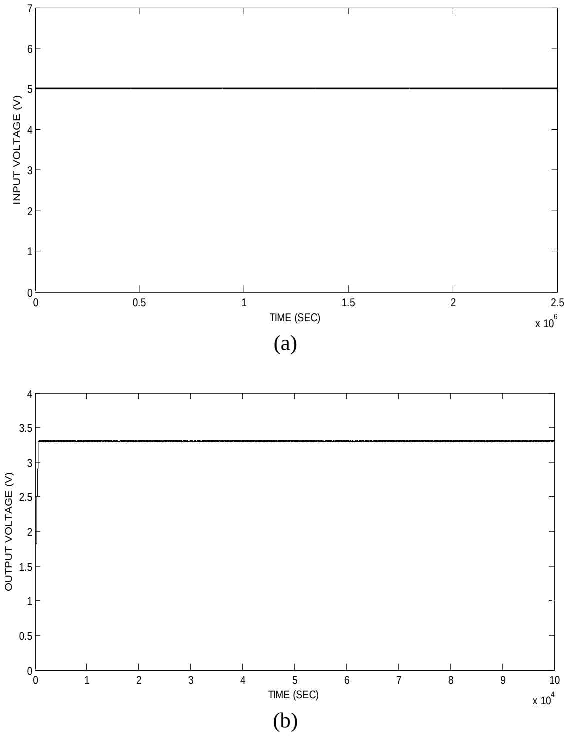


(a)

(b)

Fig. 15 (a) Input voltage and (b) Output voltage of the converter during boost operation.

The simulation model of the converter using fuzzy logic control is shown in Fig. 12. The output voltage during boost operation is 7V and during buck operation is 3.3V. The input voltage given to the converter is 5V. The input voltage and output voltage during boost operation and during buck operation are shown in Fig. 15 and Fig. 16 respectively.



(a)

(b)

Fig. 16 (a) Input voltage and (b) Output voltage of the converter during buck operation.

When PI control is used to control the integrated 2D buck-boost converter, the output waveforms was showing instability in terms of rise time and settling time. To overcome this instability in rise time & in settling time a fuzzy logic controller has been used. The fuzzy control scheme helps to remove those delay times. Rise time and settling time are also reduced.

V. EXPERIMENTAL RESULTS

A prototype of the converter is built using commercially available components to verify the operation and performance of the integrated 2D buck-boost converter. The input voltage and frequency are set to 5V and 30kHz respectively. The reference output voltage for boost operation and for buck operation is set to 7V and 3.3V respectively. The load resistance is selected as 1KΩ.

TABLE III

COMPONENTS DETAILS.

COMPONENTS	SPECIFICATION
MOSFET	IRFZ44
DIODE	IN4007
DRIVER	TLP250
VOLTAGE REGULATOR	L7805
VOLTAGE FOLLOWER	LM324

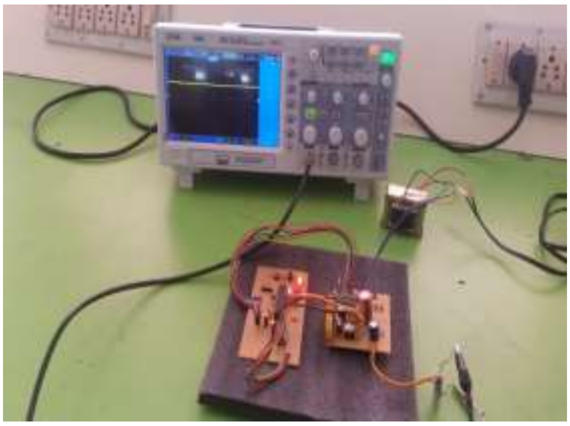


Fig. 17 Experimental setup.

The various components used in the prototype of the converter are presented in the earlier section. The aim of this hardware setup is to verify the working of the integrated 2D buck-boost converter and to provide a control using PI control. The controller used is dsPIC30F2010 for controlling the switching of the dc-dc converter. The output is analyzed with the help of DSO. Components details are shown in TABLE III.

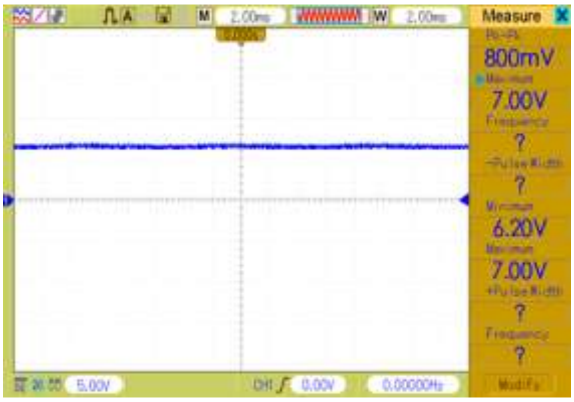


Fig. 18. Output voltage during boost operation.

The experimental setup is shown in Fig. 17. The measured output voltage for boost operation and buck operation are shown in Fig. 18 and 19 respectively. It can be seen that 5V dc input voltage is successfully boosted to 7V and bucked to 3.8V. The duty ratios of the converter are kept to be the same. The PWM gate-pulses given to the two switches are shown in Fig. 20.

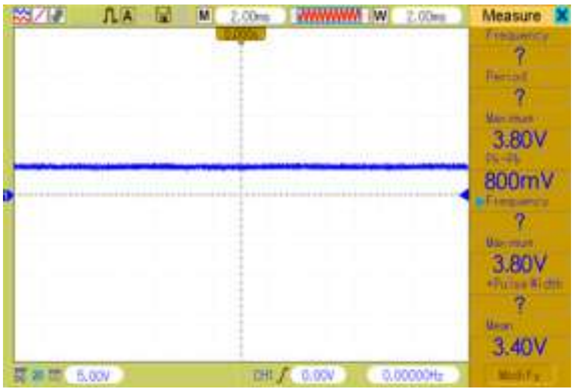


Fig. 19. Output voltage during buck operation.

Fig. 20. Gate pulses to S_1 and S_2.

VI. CONCLUSION

The proposed buck–boost converter, combining the KY converter and the traditional SR buck by using the same power switches, has a positive output voltage. Furthermore, this converter always operates in CCM inherently, thereby causing variations in duty cycle all over the load range not to be so much, and hence, the control of the converter to be easy. Such a converter possesses the non-pulsating output current, thereby not only decreasing the current stress on the output capacitor but also reducing the output voltage ripple. The proposed converter is controlled by fuzzy logic control. Based on the analysis and design equations, a prototype of the converter is developed. The converter is successfully operated to step-up and step-down the dc input voltage.

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