DESIGN AND CONTROL OF BIDIRECTIONAL SOFT SWITCHING DC-DC CONVERTER FOR HEV APPLICATIONS

K.C.RAMYA[1] V.JEGATHESAN[2]
[1]Research Scholar, Department of Electrical and Electronics Engineering, Karunya University, Coimbatore, India[1]
[2]Associate Professor, Department of Electrical and Electronics Engineering, Karunya University, Coimbatore, India[2]
Email id: ramya2614@gmail.com

Abstract: *For hybrid electric vehicle (HEV) applications, there is a need to transfer energy between battery and motor drive. Hence a bidirectional converter is required to control power flow in both motoring and regenerative braking operation so that the efficiency of the system increases. Due to compact size and weight of the bidirectional DC-DC converter (BDC), the interest is focused to transformer-less BDC. This work proposes a high efficient BDC to achieve high efficiency with reduced switching losses. The proposed converter is based on a bidirectional half-bridge type buck-boost topology along with a resonant inductor, two resonant capacitors and two parallel capacitors forms a closed loop converter for motor drive system. The proposed converter has no additional switch for soft switching of the main switch. Thus, the designed system is verified, simulated using MATLAB Simulink and the performance of the various control approaches including PI; Fuzzy and Neural control for converter is analyzed in terms of rise time and settling time. The simulation results are therefore verified with the experimental results.*

Key words: *BDC, PI controller, ZVS, Fuzzy and Neural controller, Efficiency.*

1. Introduction

Battery fed electric vehicles are commonly being used for HEV applications due to guaranteed load leveling, zero emission, better transient operation and energy recovery during braking operation. Hence bidirectional converter is required to connect the battery to the DC motor drive system. While implementing a BDC in applications, the converter should be smaller in size and lighter in weight. If the size of conventional converter is reduced, the switching frequency will be increased. This results in higher switching losses. In order to reduce switching losses that occur from the switch operation, many soft switching methods such as ZVS (zero voltage switching) and ZCS (zero current switching) have been introduced [4-10]. In the case of conventional bidirectional DC-DC converter in Fig.1, the main switches operate under hard switching condition during boost mode and buck mode. The efficiency of this system is reduced due to switching loss. Hence in order to overcome this drawback of the conventional converter, a novel bidirectional converter is proposed.

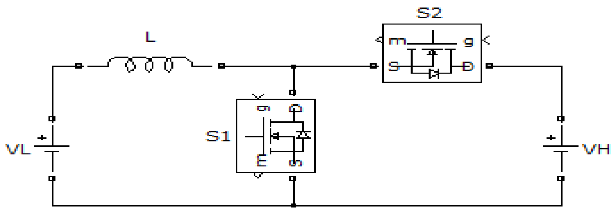

Fig. 1: Conventional DC-DC boost/buck converter

Thus the proposed converter consists of half bridge topology along with resonant capacitors and resonant inductor. The proposed converter can achieve ZVS for all switches with help of resonant circuit. A buck-boost DC-DC converter with a robust control strategy used in battery-operated electric vehicles must provide a regulated DC output voltage under varying loads or when the battery charge state varies as the input voltage varies. Generally, a conventional control solution does not meet the requirements of the robust performance. The introduction of soft computing techniques (SCT) has brought a new era in the industrial drive. Various SCT based heuristic controls have shown a good prospect to improve the performance of buck-boost DC-DC converters.

This work proposed robust intelligent controllers such as fuzzy and neural controller to control the DC-DC converter for HEV applications. The obtained results are compared, in terms of start-up behavior and robustness to disturbances with that of the conventional converter.

2. Proposed bidirectional DC-DC converter

The circuit configuration of proposed BDC is shown in Fig. 2. In this proposed model, the switching loss can be reduced by adding passive elements to the conventional converter. The auxiliary circuit unit comprises of resonant inductor and resonant capacitors. This auxiliary circuit affords ZVS function and it cancels the ripple component present in the main inductor current irrespective of the power flow direction [11,12].This converter has two operation modes namely – step up and step down mode.

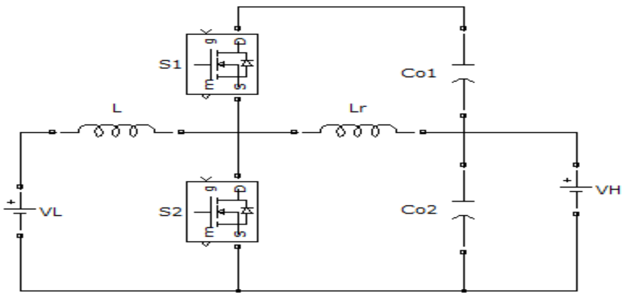

Fig. 2: Circuit configuration of proposed BDC

During step up mode, the ZVS condition is obtained by turning ON the switch S_1 and by switching OFF the switch S_2. Even though the inductor current level falls below zero, it flows continuously through the main inductor. When the level of the current crosses zero, there will be a change in direction of current. During step down mode, the performance of the switch S_1 and S_2 is reversed but is analysis is analogous to that of step up mode.

The proposed BDC transfers the power from input side, V_L to output side, V_H in step up mode whereas the power from output to input side is transferred during step down mode. During step up operation, the switch S_2 acts as a main switch whereas the switch S_1 acts as an auxiliary switch. Similarly, during step down process, the switch S_1 functions as a main switch and switch S_2 functions as an auxiliary switch. The switches S_1 and S_2 remains ON, whenever the current flows through anti-parallel diodes. Correspondingly, the conduction loss of the MOSFET is very low because of $R_{DS(ON)}$ value which is assumed to be low. Energy storable devices such as battery or Super-capacitor can be applied in the low voltage side whereas the converter high voltage side is associated with the inverter based systems.

3. DESIGN OF FUZZY CONTROLLER

Fuzzy logic control (FLC) has gained much interest in the application of system control for the past few decades. It has a real time basis as a human type operator, which makes decision on its own basis. The controller can incorporate easily the dynamic changes of the system due to the operating point shifting; hence it can tackle efficiently nonlinearity of any system. A Fuzzy Interface System (FIS) can utilize human expertise by storing its essential components in knowledge base, and perform fuzzy reasoning to infer the overall output value. However, there is no systematic way to transform experiences of knowledge of human experts to the knowledge base of a FIS. For building a FIS, the fuzzy sets, fuzzy operators and the Knowledge base has to be specified. The main feature of FLC is that it is governed by symbolic rules generally if-then rules and qualitative fuzzy variables and values. It deals with linguistic variables. Fuzzy logic approximates the relation between variables regardless of their analytical dependence. The fuzzy controller shown in Fig. 3 is composed of the following elements:

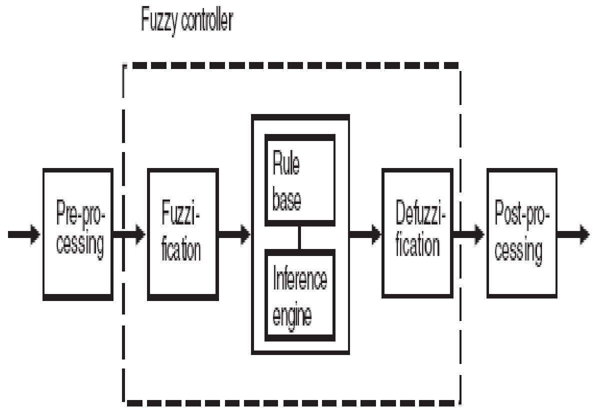

Fig. 3: Block diagram of fuzzy logic controller

1) A rule-base (a set of if-then rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.
2) A fuzzy inference engine which emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant.
3) A fuzzification interface, which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.
4) A defuzzification interface, which converts the conclusions of the inference mechanism in to actual inputs for the process.

In this fuzzy controller, Mamdani's fuzzy inference method is adopted. The conversion of fuzzy values is represented by membership functions. In order to estimate the degree of membership of input values, a triangular membership functions are preferred because of its simplicity. Fig.4 indicates the membership functions are triangle ones having linguistic labels of NB (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Large) are shown in Fig. 4(a), Fig. 4(b) and Fig. 4(c) respectively.

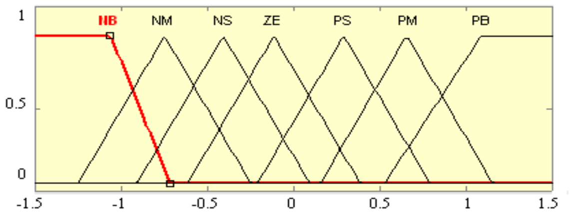

Fig. 4a: Membership functions for *e*

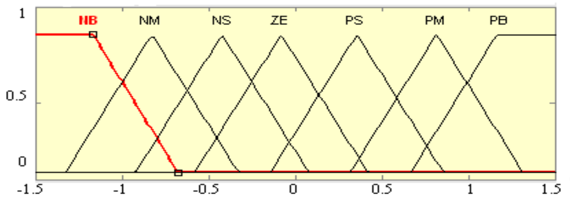

Fig. 4b: Membership functions for Δ*e*

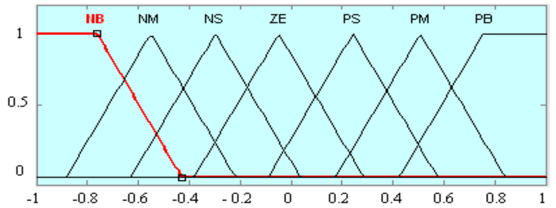

Fig. 4c: Membership functions for Δu

Rules form the basis for the fuzzy logic to obtain the fuzzy output. The rule-based form uses linguistic variables as its antecedents and consequents. The antecedents express an inference or the inequality, which should be satisfied. The consequents are those, which we can infer the output. Table 1 shows the rule base of fuzzy controller. The rule base consists of 49 IF-THEN rules. The defuzzification operation is performed by the center of gravity method.

Table 1: Fuzzy Rule Base

Δe/e	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	**NB**	**NB**	**NB**	**NM**	**NM**	**NS**	**ZE**
NM	**NB**	**NB**	**NM**	**NS**	**NS**	**ZE**	**PS**
NS	**NB**	**NM**	**NS**	**NS**	**ZE**	**PS**	**PM**
ZE	**NM**	**NS**	**NS**	**ZE**	**PS**	**PS**	**PM**
PS	**NM**	**NS**	**ZE**	**PS**	**PS**	**PM**	**PB**
PM	**NS**	**ZE**	**PS**	**PS**	**PM**	**PB**	**PB**
PB	**ZE**	**PS**	**PM**	**PM**	**PB**	**PB**	**PB**

The control signal obtained from the output of the fuzzy controller controls the PWM signals applied to the converter switches.

4. DESIGN OF ANN CONTROLLER

Artificial Neural Networks (ANN) are popular learning models for their ability to cope with the demands of a changing environment. In order to train the controller block of ANN controller, user is free to input the desired values as per the operational requirements before the start of controller's training. In the initial step, the data is generated to train the controller. While data generation process, plant response follows the reference model which is necessary for training's data set to be valid. If the response is not accurate, the data set may be regenerated. If data set is acceptable the controller may be trained through 'Train Controller' option. The training of ANN controller then starts according to the given parameters. However it is done after 'Plant Identification' i.e. training the plant unit of ANN controller through the same procedure. The training of ANN controller may take significant amount of time depending upon the given parameters and processing speed. Back-propagation neural network is a multilayer feed forward network with back-propagation of an error function. A simple back-propagation neural network has only three layers - input, output and middle layer as shown below in Fig.5.

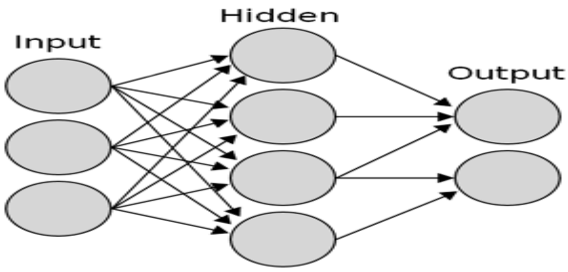

Fig.5: Layers of a feed forward neural network

The input weights are passed on to hidden layer for processing. The hidden layer passes calculated weights to the output layer. The error is presented to input layer through back propagation when actual output is different from the desired level. Hence the weights are adjusted to minimize the error through training and learning of the neural network. The process continues until the output is acceptable or pre-configured learning time is achieved. In a multi-layer feed forward neural network, more than one hidden layers may be used. Increasing the number of hidden layers provides more accuracy in results but it is harder to implement and increases the cost of system. Therefore, a careful selection of number of hidden layers is required with respect to the cost-benefit analysis.

5. SIMULATION RESULTS

To validate the performance of the proposed converter, it is verified by simulation using MATLAB simulink. Waveforms of output voltage and motor speed are obtained for both the modes of operation.

5.1 Study of closed loop control of proposed BDC in buck mode

The performance of the proposed converter can be further improved by implementing the conventional controller like PI and SCT based controllers like fuzzy & neural controllers and a comparative study is carried out to analyse their performance. Simulation results under closed loop control in buck mode of operation with motor load are discussed for an input voltage of 30V. The parameter settings for controllers are obtained using Zigler and Nicols method and are used for the simulation study.

5.1.1 PI Controlled System

The simulink model for the closed loop PI controlled system in buck mode is shown in Fig.6a. The values chosen for the controller design are given as follows: Proportional gain constant, K_p = 0.1 and Integral time constant, K_i = 5.The input DC voltage of 30V is shown in Fig.6b.The simulated output voltage is shown in Fig.6c and its value is 17V.The speed of DC motor is shown in Fig.6d.The speed settles at 180rpm.

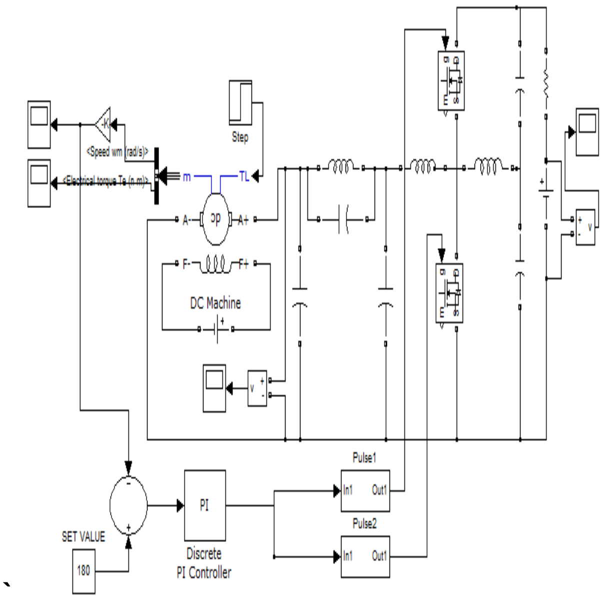

Fig.6a : Simulink model for the closed loop PI controlled system in buck mode

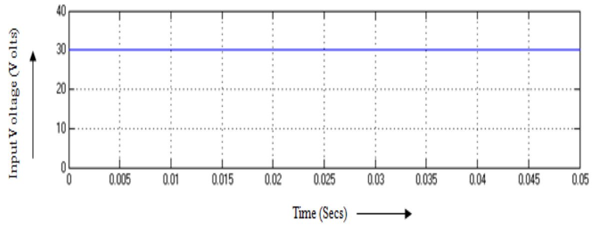

Fig. 6b: Input Voltage

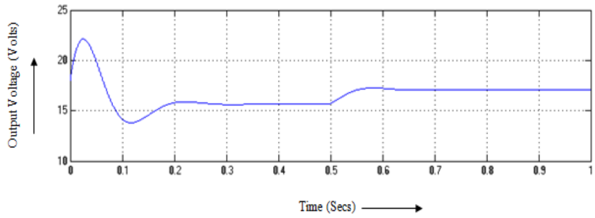

Fig. 6c: Output Voltage

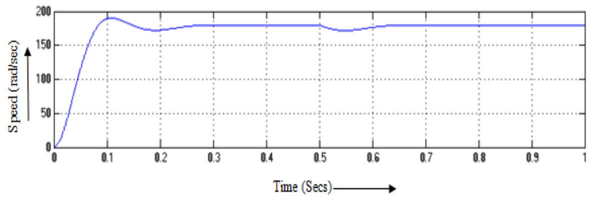

Fig. 6d: Speed waveform

5.1.2 Fuzzy Controlled System

The simulink circuit diagram for the closed loop fuzzy controlled system in buck mode is shown in Fig.7a. The simulated output voltage of 15V for 30V input is shown in Fig.7b. The speed waveform of fuzzy controlled system is shown in Fig.7c.

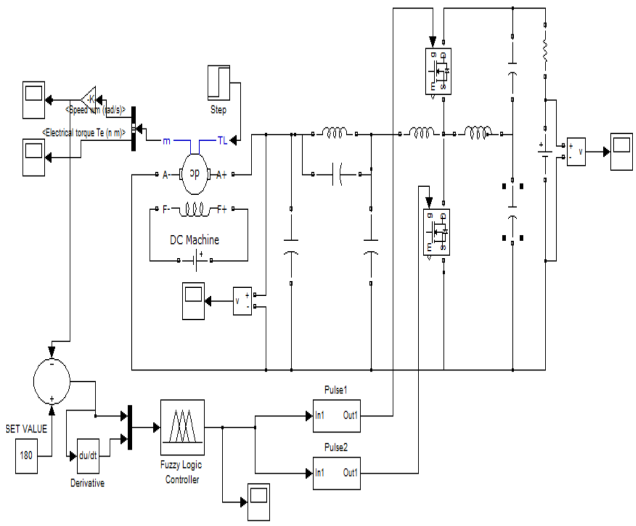

Fig.7a: Circuit diagram for closed loop fuzzy controlled system in buck mode

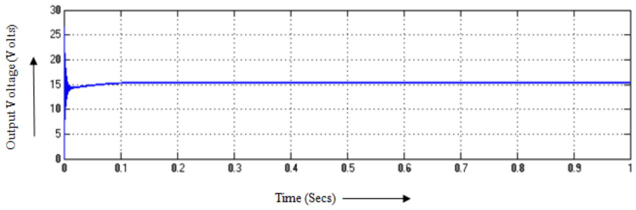

Fig. 7b: Output Voltage

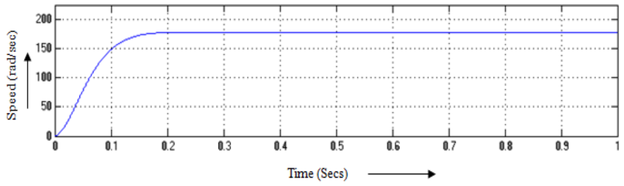

Fig. 7c: Speed waveform

From the simulated waveforms, it is evident that the settling time will be very less when compared to conventional controllers. And at the same time, the fuzzy controller exhibits faster response time with virtually no overshoot which results in improved dynamic performance of the proposed converter.

5.1.3 ANN Controlled System

An ANN controller using multilayer back propagation type is implemented to improve the performance of the NBDC furthermore. The proposed neural network is designed with the two layers. Out of these two layers, one layer is considered as input layer and the other one is as output layer. Thus the weights of the input layer associated with the adder function computes the weighted sum of the input layer. According to the weighted sum, output of the neural network is obtained.

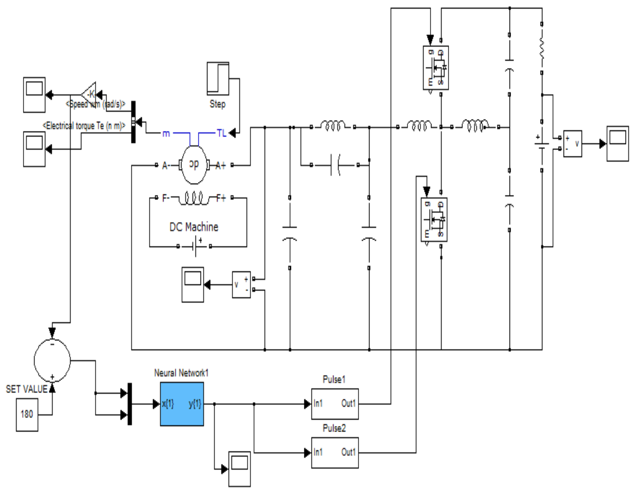

Fig. 8a: Circuit diagram for the closed loop ANN controller in the buck mode

Fig. 8a shows the simulink circuit for the closed loop ANN controlled system in buck mode is shown in Fig.8a. Fig. 8b and Fig. 8c displays voltage response and speed of the motor respectively.

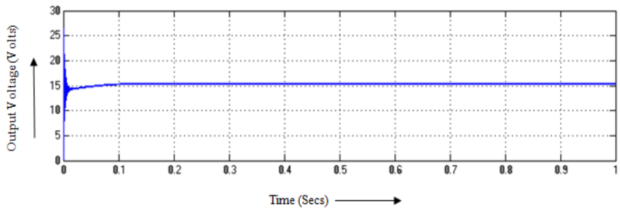

Fig. 8b: Output Voltage

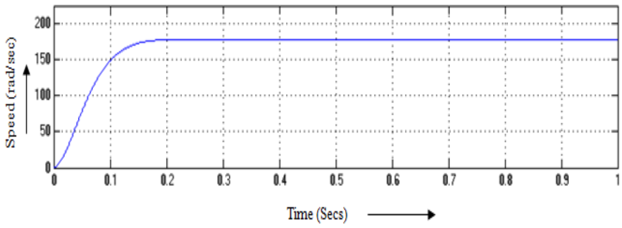

Fig. 8c: Speed waveform

From the results, it is evident that the settling time of 0.125secs is very low in buck mode for neural controller when compared to fuzzy controller whose settling time is 0.15secs. The steady state error also gets reduced to 0.8V.The faster response time as well as reduced steady state error improves the converter efficiency. The performance of ANN controller in comparison with the Fuzzy logic controller and PI controller is shown in table 2 in terms of the rise time (Tr), settling time (Ts), peak time (Tp) and steady state error (Ess) for buck mode of operation.

Table 2: Performance of buck mode - ANN controller in comparison with Fuzzy and PI controller

Proposed BDC with Controllers	**Rise time Tp**	**Settling time Ts**	**Peak time Tp**	**Steady state error Ess**
Buck mode	**(Secs)**	**(Secs)**	**(Secs)**	**(Volts)**
PI	0.1	0.11	0.63	4
FLC	0.15	-	-	0.9
ANN	0.125	-	-	0.8

From the above table, it is observed that the proposed converter with neural controller provides faster response with low steady state error. This ensures that the system can be controlled effectively with feedback. Thus from the simulation results, the choice of optimal control for the proposed converter operating in buck mode is chosen with neural controller which provides improved performance when compared to other controllers used.

5.2 Study of closed loop control of proposed BDC in boost mode

To equip the proposed converter against any disturbances, closed loop control is implemented. Thus, an analysis of converter under closed loop control is carried out with both the conventional and SCT based controllers. Simulation results for various controllers with motor load are discussed for boost mode. The input voltage applied to the converter is 15V.

5.2.1 PI Controlled System

The simulink model for the closed loop PI controlled system in boost mode is shown in Fig.9a. The values chosen for the controller design are given as follows: Proportional gain constant, K_p = 0.1 and Integral time constant, K_i = 5. The DC input voltage of 15V is shown in Fig.9b. The simulated output voltage of 31V is shown in Fig.9c. The speed of the DC motor is shown in Fig.9d and the speed settles at 330 rpm.

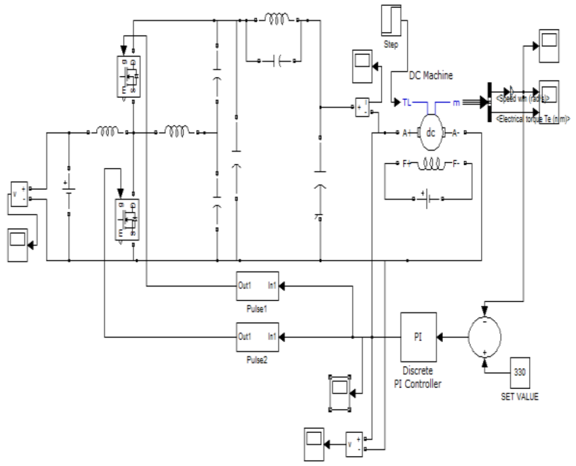

Fig. 9a: Circuit diagram for the closed loop PI controller in the boost mode

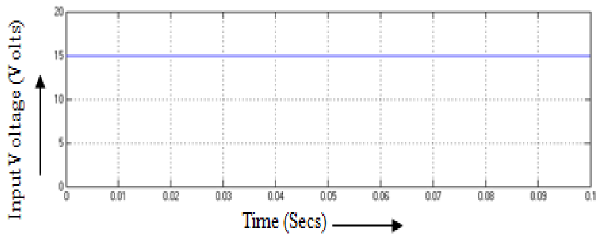

Fig. 9b: Input Voltage

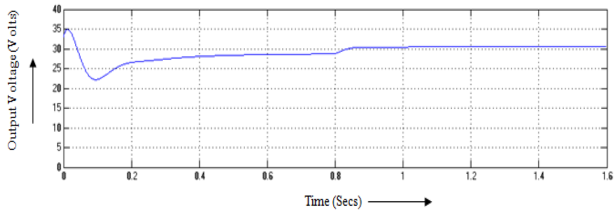

Fig. 9c: Output Voltage

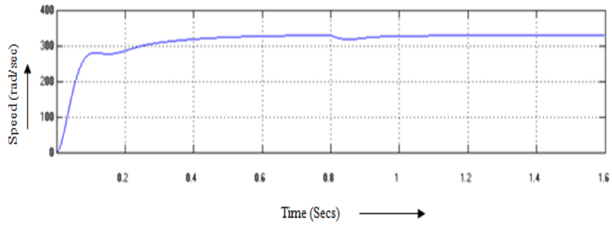

Fig. 9d: Speed waveform

The corresponding changes in the output voltage and speed are noted. The PI controller regulates the voltage and reaches its steady state condition at time t=0.85secs.

5.2.2 Fuzzy Controlled System

The simulink circuit for the closed loop fuzzy controlled system in boost mode is shown in Fig.10a. The output voltage of 30V for the input voltage of 15V is shown in Fig.10b. The speed waveform of fuzzy controlled system is shown in Fig.10c.

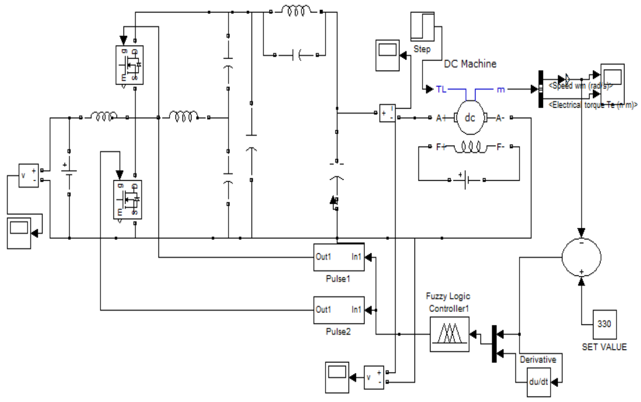

Fig. 10a: Circuit diagram for the closed loop fuzzy controller in the boost mode

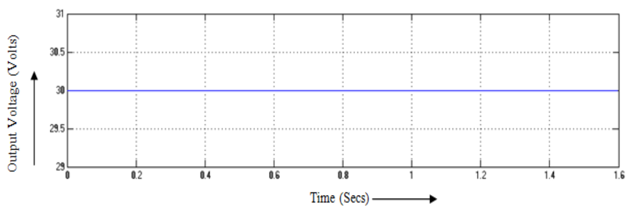

Fig. 10b: Output Voltage

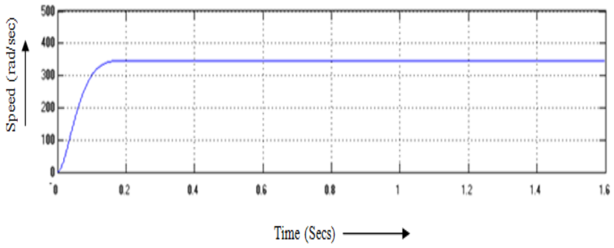

Fig. 10c: Speed waveform

From the results, it is evident that the settling time will be very less when compared to PI controller. And at the same time, the fuzzy controller exhibits faster response time with virtually no overshoot which results in improved dynamic performance of the proposed converter.

5.2.3 ANN Controlled System

The simulink circuit for the closed loop ANN controlled system in boost mode is shown in Fig.11a. Fig.11b and Fig.11c shows the waveforms of output voltage and speed waveform of ANN controller respectively.

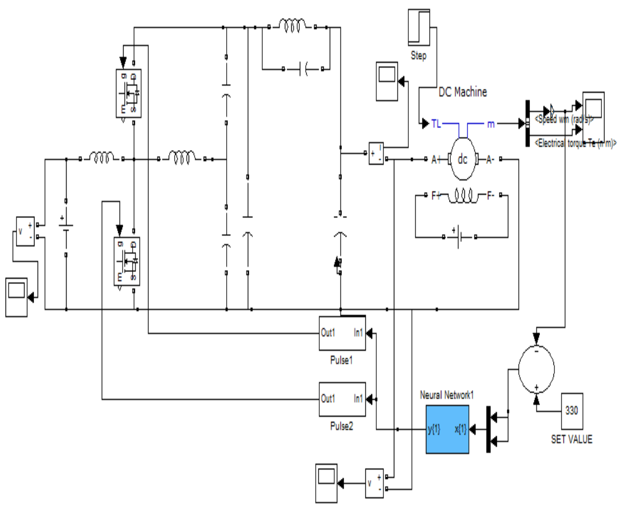

Fig.11a: Circuit diagram for the closed loop ANN controller in the boost mode

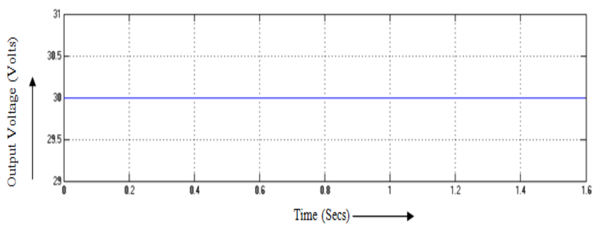

Fig. 11b: Output Voltage

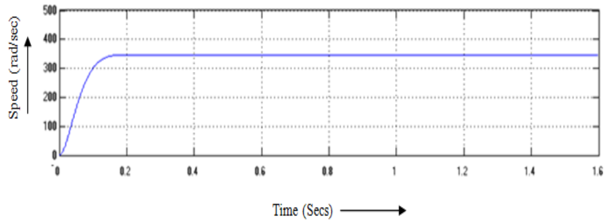

Fig. 11c: Speed waveform

From the results, it is concluded that the settling time and steady state error value is very low with neural controller when compared to other controllers. The performance of ANN controller in comparison with the Fuzzy controller and PI controller is shown in Table 3 in terms of the rise time (Tr), settling time (Ts), peak time (Tp) and steady state error (Ess) for boost mode of operation.

Table 3: Performance of boost mode - ANN controller in comparison with Fuzzy and PI controller

Proposed BDC with Controllers	**Rise time Tp**	**Settling time Ts**	**Peak time Tp**	**Steady state error Ess**
Boost mode	**(Secs)**	**(Secs)**	**(Secs)**	**(Volts)**
PI	0.15	0.38	1	5
FLC	0.08	-	-	0.10
ANN	0.06	-	-	0.10

From the table, it is observed that proposed converter with neural controller provides better settling time. Also the steady state error gets reduced considerably from PI controller to neural controller. This ensures that the system can be controlled effectively with feedback. Thus, the choice of optimal control for the proposed converter operating in boost mode is also chosen with neural controller which provides faster response with virtually no overshoots when compared to other controllers. From the investigations, it is observed that the response of ANN controlled system is superior to the response of FLC and PI based systems.

6. EXPERIMENTAL RESULTS

To test the performance of the studied BDC, a laboratory prototype circuit illustrated in Fig.12 is implemented. The proposed BDC parameters and specifications of the constructed hardware prototype are given as high-side voltage of 30 V and low-side voltage of 15V. IRF540 is used for all of the switches which provide fast switching and low on-state resistance. According to design procedure, the value of parameters chosen for prototype converter is shown in Table 4.

Table 4: Experimental Parameters

Parameter	Value
Rated low voltage	15V
Rated high voltage	30V
Main inductor	1mH
Resonant inductor	60µH
Resonant capacitors	10nF
Switching frequency	50Hz

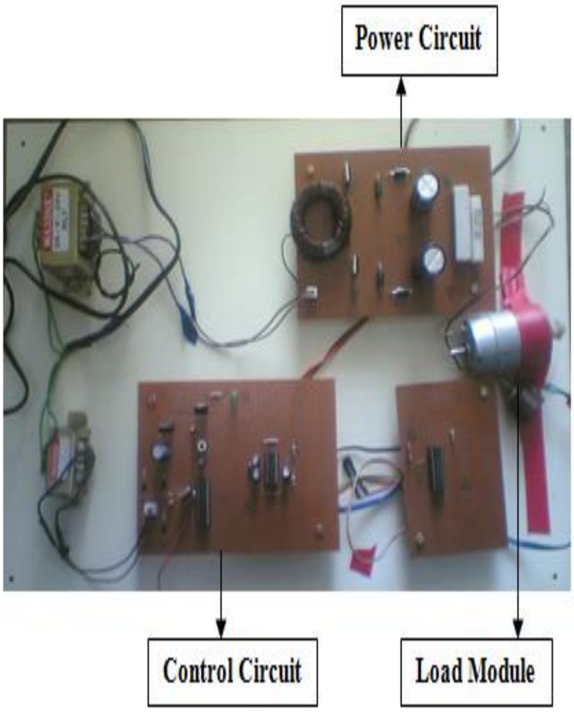

Fig.12: Prototype of the proposed converter

Fig. 13 shows the voltage waveforms of the BDC in boost and buck mode respectively. During boost mode under ZVS condition, the main switch was in OFF condition. The switch S_2 turns on under ZVS condition while current flows through anti-parallel diode. During step down mode, both S_1 and S_2 were turned ON and turned OFF under ZVS condition similar to boost mode, even though the role of switches S_1 and S_2 was altered. The gate pulse and driver output pulse for the switches are also shown in Fig.13.

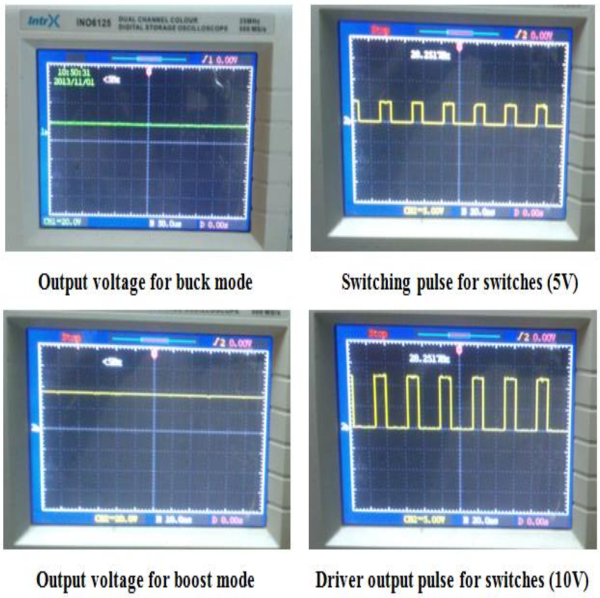

Fig.13 Experimental results of proposed BDC

Fig. 14 describes the output power and efficiency comparative plots for both step down and step up mode. The efficiency graphs of conventional BDC and proposed BDC is presented. When compared to the conventional converter, it is proved that BDC posses higher efficiency. During boost mode, maximum efficiency of about 97.6% is achieved whereas during buck mode, it is about 97.48%. From the below curves, it is inferred that the proposed NBDC topology achieves higher efficiency about 2 to 3% than conventional converter topologies.

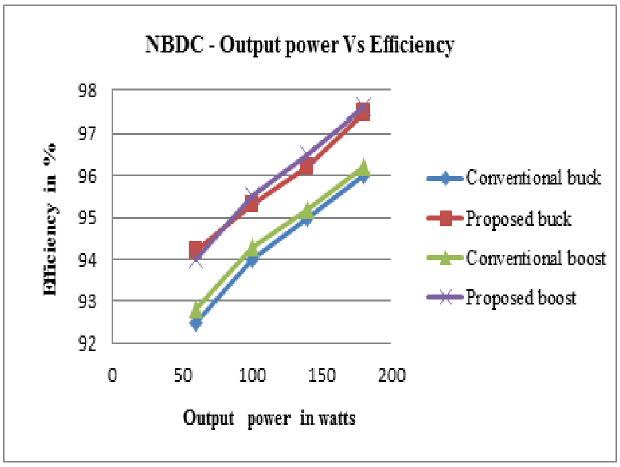

Fig.14 Proposed BDC - Efficiency graph

For all the conditions investigated, soft switching bidirectional buck-boost converter provides higher efficiency than the conventional converters.

7. CONCLUSION

This work proposes a bidirectional soft switching DC-DC converter. Circuit models were developed for both buck and boost mode. From the performance measures, it is concluded that neural network based controller is proven to be more suitable for the proposed converter among various controllers used. The performance of the BDC was measured by both simulation and hardware results. Thus the proposed BDC provides improved performance in terms of low ripple at its output, better efficiency and good regulation when compared to conventional converter.

References

1. A.AmalinRishma, P.RajaRajeswari, M.Sasikumar, "High Efficiency Modified Pulse Width Modulation Bidirectional Converters for Medium Power Drives", IJAIEM, vol. 1, no. 2, pp. 94–100, 2012.
2. Amin Mirzaei, Awangjusoh, Zainal Salam, "Design and Implementation of High Efficiency Non Isolated Bidirectional Zero Voltage Transition Pulse With modulated DC-DC converters," Elsevier- Energy 47, pp. 358–369, 2012.
3. Baburaja.C and J.Jayakumar, "Transformer less soft switching bi-directional DC-DC Chopper", International journal of Engineering and Advanced Technology, vol. 2, pp.391-395, 2013.
4. Chuan-KueiHuang, Hsiau-Hsian Nien, Koan-Yuh Chang and Wen-JerChang,,"An Optimal Designed RCD Snubber for DC-DC Converters ,"Journal of Marine Science and Technology, Vol. 18, No. 6, pp. 901-906, 2010.
5. D.-Y. Lee, M.-K. Kee, D.-S. Hyun, and I. Choy, "New zero-current-transition PWM DC/DC converters without Current Stress," IEEE Trans. Power Electron., vol. 18, no. 1, pp. 95–104, 2003.
6. Doo-Yong Jung, Sun-Hee Hwang, Young-HyokJi, Jung-Hyo Lee, Yong-Chae Jung and Chung-Yuen Won, "Soft-Switching Bidirectional dc-dc Converter with a LC Series Resonant Circuit," IEEE Trans. Power Electron ,vol. 28, no. 4, pp. 1680– 1690,2013.
7. G. Hua, C. Leu, Y. Jiang, and F. C. Lee, "Novel zero-voltage transition PWM converters," IEEE Trans. Power Electron., vol. 9, no. 2, pp. 213–219, Mar. 1994.
8. Ho-Sung Kim, Myung-HyoRyu, Ju-Won Back and Jee-Hoon Jung, "High-Efficiency Isolated Bidirectional AC-DC Converter for a dc Distribution System," IEEE Trans. Power Electron., 2013, vol. 28, no. 4, pp.1642–1654.
9. Hua Han, Yonglu Liu, Yao Sun, Hui Wang and Mei Su, "A Single Phase Current Source Bidirectional Converter for V2G Applications" Journal of Power Electronics, 2014, vol. 14, no. 3, pp. 458-467.
10. Huiqing Wen and BinSu, "Reactive Power and Soft-Switching Capability Analysis of Dual -Active – Bridge DC-DC Converters with Dual-Phase-Shift Control" Journal of Power Electronics, vol. 15, no. 1, pp.18–30, 2015
11. Hyung-Min Ryu , "High Efficient High-Voltage MOSFET Converter with Bidirectional Power Flow Legs", Journal of Power Electronics, Vol. 14, No. 2, pp. 265-270, 2014.
12. Jeong-il Kang, Sang-Kyoo Han and Jonghee Han, "Lossless Snubber with Minimum Voltage Stress for continuous Current Mode Tapped-Inductor Boost Converters for High Step-up Applications," Journal of Power Electronics, vol. 18, no. 4, pp. 621–631, 2014.
13. Jun-Gu Kim, Seung-Won Park, Young-Ho Kim, Yong-Chae Jung and Chung-Yuen Won "High efficiency bidirectional soft switching DC-DC converter", IEEE International Power Electronics Conf. 2905-2911, 2010.