A High Performance DC-DC Converter with Battery Charging Circuit.

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ABSTRACT

This paper introduces a bi-directional DC-DC converter with adaptive fuzzy logic controller (AFLC). Bi-directional power flow is obtained by the same power components and provides a simple, efficient, and galvanically isolated converter. In the presence of DC mains, the converter operates as buck converter, powers the down stream converter, and also charges the battery. When the DC mains fails, the converter operates as a boost converter and the down stream converter is fed by the battery. In both modes the power switches are controlled by the Pulse Width Modulation (PWM) technique and the pulses are generated by the application of fuzzy logic with an adoption algorithm. The proposed converter is simulated using MATLAB® and a laboratory prototype is developed to validate the simulation results.

(Keywords: DC-DC converter, fuzzy logic controller, AFLC, bi-directional power flow, battery, MATLAB)

INTRODUCTION

Bi-directional DC-DC converters are involved in power flow between two DC sources. They allow power flow in both directions without a change in the polarity of the voltage. They are used in DC un-interruptible power supplies and battery charging circuits. In the literature, bi-directional power flow is obtained by constructing individual converters for each direction of power flow [5]. Then they are implemented by soft switching [7] and resonant techniques [6], but they increase the component count and circuit complexity. It can also miss the soft switching signals at light loads.

To overcome these difficulties, a bi-directional converter which is a merge of a half bridge converter and a push-pull converter is proposed. It claims the following advantages: They are (i) low stress on switches, ii) galvanic isolation is achieved, and (iii) there is a reduced components count. A MOSFET switch is used in this converter. The bi-directional power flow property of MOSFET enables power flow of the proposed converter in either direction using only one transformer. The dynamic behavior of this converter is also improved by the fuzzy logic.

Generally, any of the intelligent techniques improves the dynamic performance of the converter. Neural Networks (NN) can be seen as an alternative used to model and control nonlinear and linear systems where the traditional methods fail [2]. The problem in neural network designs is often seen on two perspectives: the first is the number of examples necessary to obtain a good generalization; the second is the size of the neural network.

The identification of the parameters of the NN, otherwise called training, is often carried out by the back propagation algorithm [4], which is based on the minimization of the error of training and the chaining rule. This algorithm uses a gradient decent showed and several disadvantages such as the slowness of convergence, the sensitivity to the local minima, and the difficulty in regulating the training parameters. Approaches were proposed to improve the back propagation algorithm, such as, modification or decentralization of the step size, use of quasi-Newton algorithms [4], algorithms genetic [4], etc. On the other hand, the approximation capability of a neural networks is closely related to the number of the neurons in the hidden layer. One usually seeks a compromise between the accuracy and the complexity of the network. Therefore, fuzzy logic was chosen for converter control in this paper.

The fuzzy-based controller designing strategy started nearly a decade ago. In 1994, an FLC controller [10] was proposed for simple DC-DC converters. This was implemented by using a Digital Signal Processor (TMS320C50) in 1996 [9]. In the year 1997, neural network control was designed for DC-DC converters [4]. In 2006, different control strategies have been proposed to control DC-DC converters and were implemented by using microcontrollers and specialized hardware. In recent years, neurofuzzy controllers and adaptive fuzzy logic controllers simplified the process of controller design and provide efficient control. More interest has been developed in the intelligent technique based controllers for most of the circuits because of i) simplicity in controller development, ii) possibility of automated control, and iii) need of less skilled labor.

This paper proposes a new topology of DC/DC converter with bi-directional power flow which reduces the cost of the converter and improves the efficiency. The intelligent technique based controlling strategy improves the dynamic behavior of the proposed converter.

The paper is organized as follows: we present the description and operating modes of the proposed converter; the paper then presents design considerations of the controller; this is followed by an explanation of the simulation results and various current and voltage waveforms obtained by simulation. The paper then presents the experimental results of the proposed converter constructed and offers the authors' conclusions.

PROPOSED CONVERTER

This paper proposes a bi-directional DC-DC converter controlled by Adaptive Fuzzy Logic Controller. Adoptive fuzzy logic denotes fuzzy logic with an adoption algorithm. Fuzzy logic controller is constructed and adoption algorithm is imposed on this controller. The overall block diagram of the proposed converter is shown in Figure.1. This includes the internal blocks of the fuzzy logic controller, bi-directional DC/DC converter with sensing and error producing component.

The block diagram of bidirectional converter proposed in this paper is shown in Figure 2. It includes two converters topologies for power flow in either direction. Both the topologies are involved in power flow to the load irrespective of the presence of the main supply. The power circuit of the converter is shown in Figure 3.

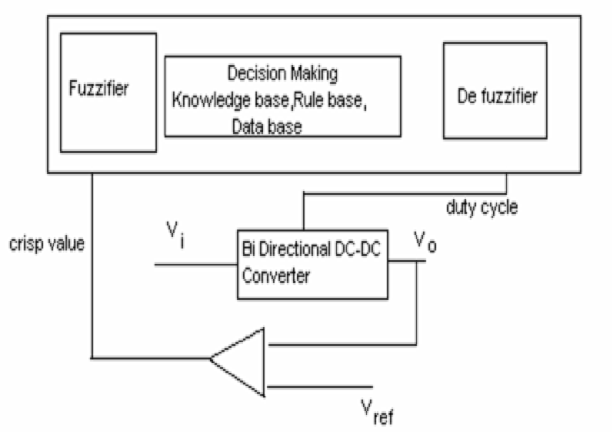


Figure 1: Block Diagram of Fuzzy Logic Controlled Converter.

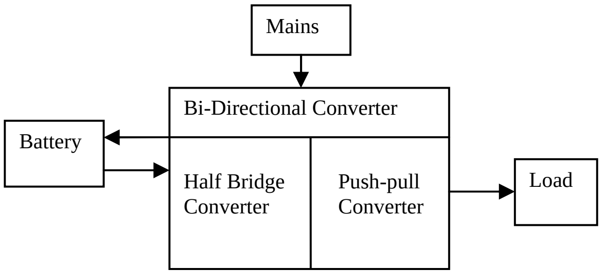


Figure 2: Block Diagram of Proposed Converter.

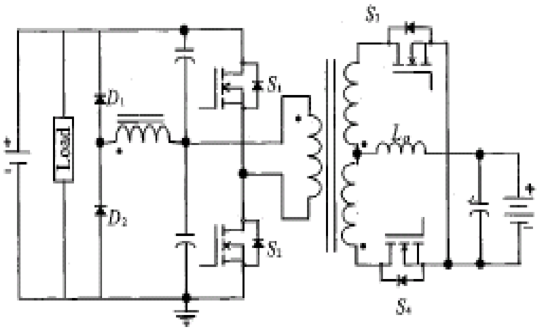


Figure 3: Power Circuit of Proposed Converter.

In the circuit proposed, the primary side of the transformer is connected with a half bridge converter which includes the switches S1 and S2 and is fed by the power supply. The secondary of transformer is connected to the switches S3 and S4 and forms a push-pull topology. The converter operates in two modes. In the forward mode, operation switches S1 and S2 are operated and S3 and S4 are switched off. The converter exhibits the operation as a buck converter. In back up mode, S3 and S4 are switched and the switches S1 and S2 are in the off condition. Operation of the converter in this mode is similar to a boost converter, with individual switching signals applied for individual switches.

The following assumptions were also made for the proper analysis of the converter:

i. The switches and diodes are ideal.

ii. Transformer is ideal and the turns ratio is one.

iii. All the voltages and currents applied are periodic.

The proposed half bridge and push-pull combined topology is advantageous in the following aspects when compared to the conventional converters:

- The switches are subjected to voltage stress only equal to the DC input voltage. But in the conventional push-pull converter the switches are subjected to voltage stress twice the input voltage.

- In low power conditions usage of two switch half bridge topology reduces the size of LC filter required, when compared with four switch full bridge converter topology.

As per the block diagram of the converter shown in Figure 2, the switches are controlled by the error signal produced. So the required duty cycle variation of the switching signal depends on the input voltage of the converter and battery voltage. It is given by the expressions shown below.

Forward mode:

$$d_{min} = \frac{V_{battmax}}{V_{smin}} \qquad d_{max} = \frac{V_{battmax}}{V_{smax}}$$

Back up mode:

$$d_{min} = \frac{Vs-V_{battmin}}{V_s} \qquad d_{max} = \frac{1-2V_{smin}}{V_s}$$

d_{min}-minimum value of duty cycle;
d_{max}-maximum value of duty cycle;
$V_{battmax}$-Maximum value of battery voltage;
$V_{battmin}$-Minimum value of battery voltage;
V_{smin}-Minimum value of mains supply voltage;
V_{smax}-Maximum value of mains supply voltage;
V_s-Output voltage in backup mode.

CONTROLLER DESIGN

The process of fuzzy logic controller design includes the following steps:

i. Fuzzification - Process of representing the inputs as suitable linguistic variable.

ii. Decision making - Appropriate control action to carried out. It is based on a knowledge-base and rule-base. The knowledge-base and rule-base are the details about the linguistic variables and control rules

iii. Defuzzification - Process of converting fuzzified output into crisp value. The inputs to the FLC are error signals and differences of error signals. The output is the duty ratio of the switching signal.

$$\mathbf{e=V_{ref}-V_o;\ \ d(t)= d(t-1)-d(x(t))}$$

d(t-1)=Duty cycle at $(t-1)^{th}$ instant;
V_o=Output Voltage;
d(x(t))=Change in duty cycle;
V_{ref}=Reference Voltage;
d(t) =Duty cycle at t^{th} instant;
e=error signal.

All of the linguistic variables are assumed to have the same number of linguistic values. The shrinking span membership function algorithm, proposed by Chies and Hsieh, is used to construct FLC without need of expert presence. This algorithm involves the process of arranging the membership functions of a linguistic variable in an orderly manner across the universe of discourse.

The shrinking factor (S_f) decides the span of member ship function. By applying various values of S_f to one linguistic variable, the most suitable membership function can be decided.

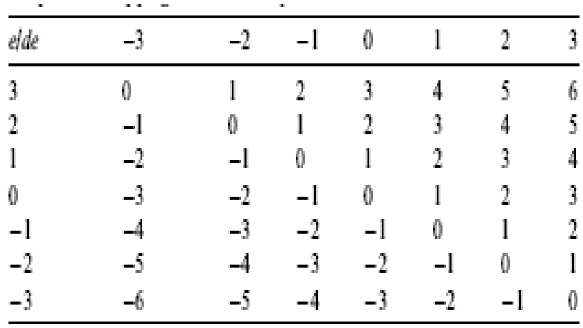
A Mamdani-type controller is chosen for this application and the basic rule of this type of controller is:

IF e is A and de is B THEN d(t) is C

Here, A and B are fuzzy subsets and C is a fuzzy singleton. Each universe of discourse is divided into seven subsets such as Positive Large (PL), Positive Medium (PM), Positive Small (PS), Zero (ZE), Negative Small (NS), Negative Medium (NM), and Negative Large(NL).

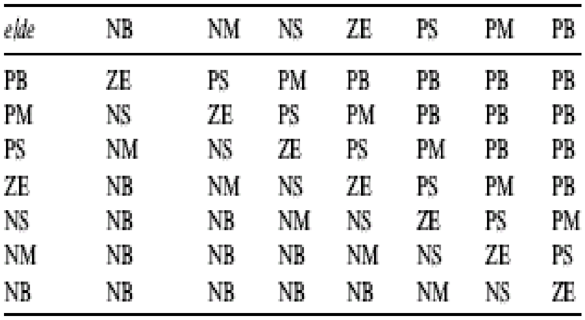
The rule-base for the corresponding membership functions is decided by index representation method as shown in Table 1. Table 2 shows the linguistic label representation of the rule-base.

Table 1: Rule Mapping by Index Representation.



e/de	−3	−2	−1	0	1	2	3
3	0	1	2	3	4	5	6
2	−1	0	1	2	3	4	5
1	−2	−1	0	1	2	3	4
0	−3	−2	−1	0	1	2	3
−1	−4	−3	−2	−1	0	1	2
−2	−5	−4	−3	−2	−1	0	1
−3	−6	−5	−4	−3	−2	−1	0

Table 2: Labels of Linguistic Variables.



e/de	NB	NM	NS	ZE	PS	PM	PB
PB	ZE	PS	PM	PB	PB	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PS	NM	NS	ZE	PS	PM	PB	PB
ZE	NB	NM	NS	ZE	PS	PM	PB
NS	NB	NB	NM	NS	ZE	PS	PM
NM	NB	NB	NB	NM	NS	ZE	PS
NB	NB	NB	NB	NB	NM	NS	ZE

The center of gravity method of de-fuzzification is applied to obtain a crisp result from the linguistic values obtained according to the rule-base.

$$du = \frac{\Sigma W_i C_i}{\Sigma W_i}$$

du denotes the change in duty ratio inferred by the i^{th} rule; C_i denotes fuzzy singleton; and W_i denotes the weighting factor. The inputs to the AFLC are the training data from model file and the outputs are the membership functions. It adopts various parameters according to the training data fed through the pattern file. The duty ratios of all four switches must be determined in order to calculate other circuit parameters. The constraints to be kept in mind are that the output (battery) voltage in the forward mode can, at most, be equal to half the input DC bus voltage and in the backup mode the output voltage (at the DC bus) must be at least equal to the input (battery) voltage. Also, the maximum theoretical duty ratio of S_1 and S_2 in the forward mode must be less than 0.5, while the minimum theoretical duty ratio of S_3 and S_4 in the backup mode must be greater than 0.5.

The duty ratios are dependant on the voltages at the input and the output in both operating modes. The algorithm calculates the overall error index (e_{io}) and updates the parameters to make e_{io} to be zero. Finally, application of AFLC ensures desired operation of proposed converter.

SIMULATION RESULTS

The proposed converter is simulated using MATLAB® package. The rating of converter in both the modes given in Table 3.

Table 3: Rating of Converter in Both the Modes.

Parameter/Mode	**Forward Mode**	**Backup mode**
Input Voltage	300-400V	No mains supply
Output voltage	300-400V	350V
Output Power	100W	300W
Operating Frequency	100KHz	100KHz

The waveforms are repetitive for every switching cycle. The waveforms is divided into many time intervals and analyzed.

Forward mode operation is divided into four time intervals. The waveforms are shown in Figure 4.

During interval t_{1f} $V_s/2$ voltage appears across primary winding and the primary current builds up. In interval t_{2f} there is no voltage across the primary and secondary winding, so there is no power transfer and the converter performs freewheeling action. Half the input voltage appears across switches.

In the third interval t_{3f} the operation is similar to interval t_{1f} and the secondary side diodes offers rectification. In the interval t_{4f} the operation is similar to interval t_{2f}.There is no primary side conduction in this interval. In all these time intervals the reverse voltage appears across switches does not exceed $V_s/2$.

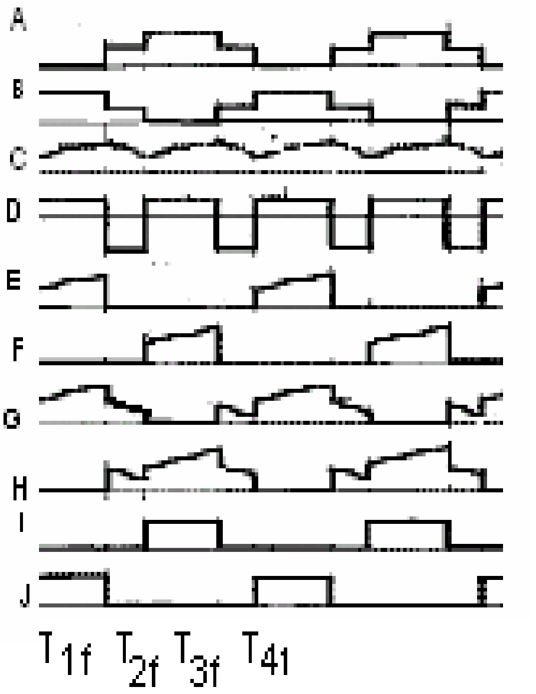


Figure 4: Waveforms During Forward Mode Operation: *A) Voltage across switch S_1, B)Voltage Across Switch S_2, C) Load Current, D) Load Voltage, E) Current through S_1, F) Current through S_2, G) Current through Body Diode of S_3, H) Current through Body Diode of S_4, I) Voltage Across Switch S_4, J)Voltage Across Switch S_3.*

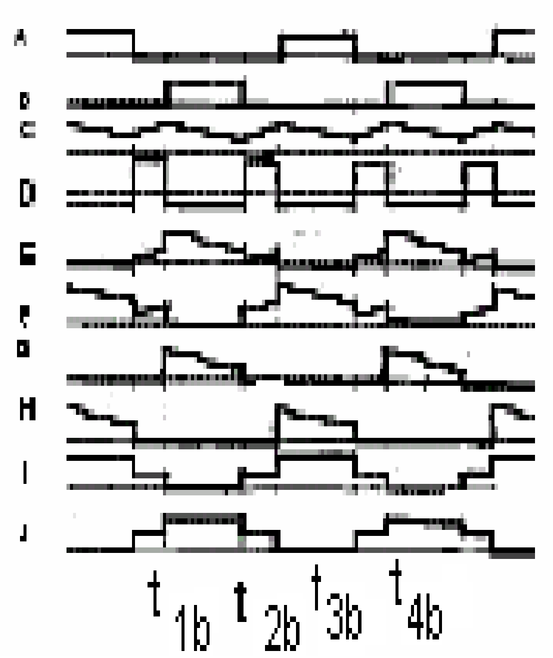


Figure 5: Waveforms During Backup Mode Operation: *A) Voltage Across Switch S_3, B) Voltage Across Switch S_4, C) Load Current, D) Load Voltage, E) Current Through S_3, F) Current Through S_4, G) Current Through Body Diode of S_1, H) Current Through Body Diode of S_2, I) Voltage Across Switch S_2, J) Voltage Across Switch S_3.*

Back up mode operation is also divided into four intervals. The waveforms are shown in Figure 5. In the first interval, t_{1b}, the transformer secondary is subjected to short circuit. The inductor stores energy and the total battery voltage appear across the inductor. The bulk capacitors provide output load power. In the second interval, t_{2b}, the energy stored in the inductor is transferred to load. Equal voltage appears across primary and auxiliary winding, so both the capacitors get charged simultaneously. In the interval t_{3b}, the operation is similar to interval t_{1b}. In the last time interval, t_{4b}, the operation is similar to the t_{2b} interval. The diodes causes equal charging of capacitors.

In the simulation of the AFL controller, a pattern file is generated initially. It consists of three vectors, two inputs error and change of error, and the output vector is the change of duty cycle. Seventy-two epochs were performed and the error measure is $9.3X10^{-5}$. The shrinking factor (Sf) value is 0.35. Figures 6(a) and 6(b) show the waveforms of input and output vectors obtained during simulation.

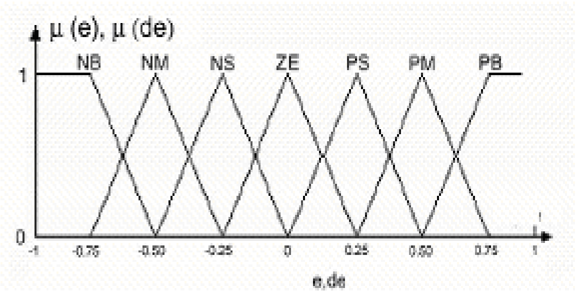


Figure 6 a: Input Vectors (i.e., Error and Change in Error).

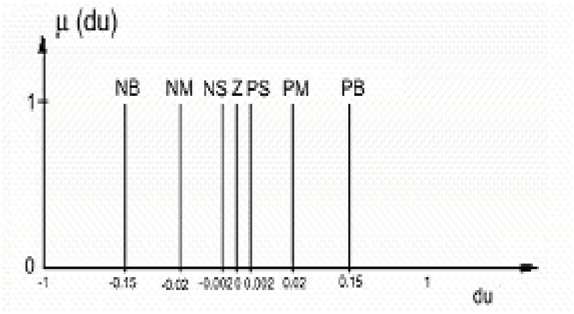


Figure 6 b: Output Vector (i.e., Change in Duty Cycle).

The results indicate that this method provides an easy and systematic way in designing the AFLC. The generated membership functions and rule base are general and could be used for any without any modification.

HARDWARE RESULTS

A laboratory prototype of the above proposed converter was developed with the help of a ST52T420 microcontroller. It is an 8 bit microcontroller. It effectively performs fuzzy logic and Boolean operations. Components used in prototype construction are tabulated in Table 4. The static performance was studied for both the forward and backup modes. The dynamic response of the converter under transient conditions of step changes in load and switchover from charging to backup mode is illustrated.

Table 4: Specifications of Components used in Prototype.

S. No.	Component	Rating/Model
1	Diode	IN4007A
2.	MOSFETS	IRF840
3.	Capacitors	150μF
4.	By pass capacitor	470μF
5.	Inductors	2mH&380μH

Wave forms of various currents and voltages are obtained for both the modes of operation. Figure 7 shows the photograph of the constructed converter.

Figure 7: Top-view Photograph of the Constructed Converter.

Figure 8 shows the waveforms of battery voltage, inductor current and transformer charging current in the forward mode operation when there is power available in mains.

Figure 9 shows the waveforms in back up mode operation. Figure 10 shows the waveforms of converter when its switching from forward to back up mode.

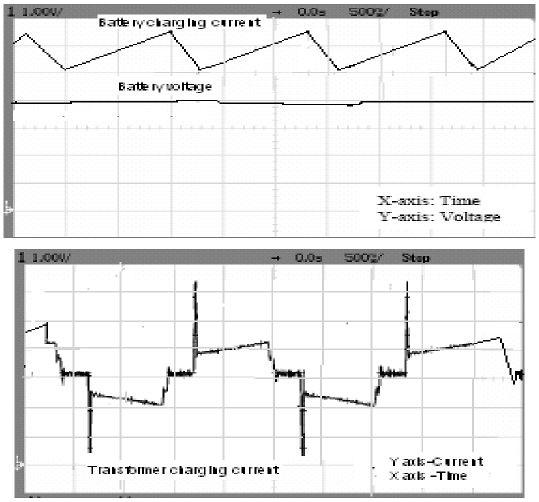


Figure 8: Battery Charging Current, Battery Voltage, and Transformer Charging Current Waveforms in Forward Mode Operation.

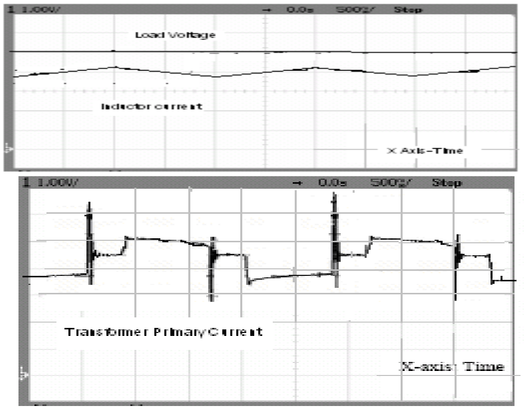


Figure 9: Back-up Mode Load Voltage, Inductor Current, and Transformer Primary Current.

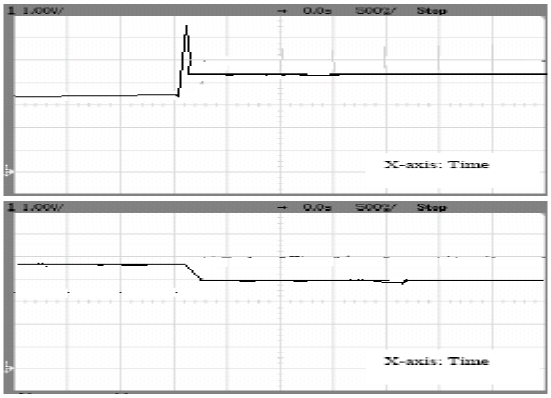


Figure 10: Waveforms of Inductor Current and Load Voltage when Switching from Forward to Back-up Mode of Conduction.

Figure 8 shows the experimental waveforms for the forward/charging mode, at 75% load, with the converter operating at 100 kHz (360 V, battery power 85W). The DC mains supplies load power and charges the battery to 54.5V, the battery charging current 1.55A is constant with relatively small ripple as desired.

Figure 9 shows the relevant waveforms during steady state operation of the converter in the backup/current-fed mode at 75% rated load. The battery voltage, 50V and load power, 190W. The battery discharges to boost the voltage level of the DC bus to 325V,thereby powering the load.

Current spikes are observed in the transformer primary current, in the forward mode and backup modes. These are due to the reverse recovery of the diodes. These spikes are not present in the simulated waveforms because the diodes considered in simulation are ideal diodes. The higher voltage drop across them will not greatly effect the converter efficiency because of the low currents flowing through them in both operating modes when providing load rectification.

Certain applications may require the converter to start operating in the backup mode when the hold up capacitors and are not charged. Under such conditions, as the duty cycle of and is increased to build up the load (DC bus) voltage, current in the inductor continues to rise with the switches operating at maximum duty cycle. This continuous increase in the current results in a switch current that exceeds the rated value and can permanently damage the switch. This problem can be avoided by adding a parallel combination of a relay and resistor, in series with the battery when starting up in the backup mode, with no output voltage. The series resistor limits the previously increasing inductor current. Once the output capacitors are charged the resistor is bypassed by the relay.

Transient performance of the converter is evaluated under the condition of switchover from Forward to Backup Mode When the Battery Is Charged. Figure 10 shows the switchover at 75% load, with the battery charged at 53 V and therefore drawing minimal current. The bus voltage is 360 V in the forward mode and is regulated at 325 V in the backup mode, which is within the load converter's working input voltage range of 300–400 V. On AC mains failure, the voltage at the DC bus starts to drop. As soon as the bus voltage is detected below 325 V, the converter begins operation in backup mode and regulates the bus voltage at 325 V. Other values of the regulated bus voltage in the backup mode are possible by appropriate changes in the line and bulk detection circuitry. Figure10 shows that inductor current, changes direction and reaches a steady state value in a very short duration. This is due to the non-ideal components involved in prototype construction. But in simulation circuit this shows the smooth variation and the converter thus provides seamless transition from forward to backup mode.

CONCLUSION

In this paper the design methodology of a bidirectional DC-DC converter with adaptive fuzzy logic controller is proposed and evaluated by constructing a laboratory prototype. The adaptive controller is implemented on an 8-bit microcontroller. Experimental results of the converter shows the effectiveness of described adaptive fuzzy logic controller and satisfactory results without pre-constructed rules of any expert. The prototype shows good steady state operation and smooth switchover between modes. It shows low part count and galvanic isolation due to its bidirectional power flow mode.

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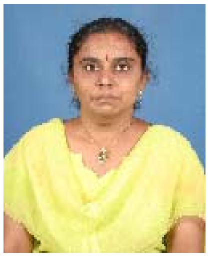

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SUGGESTED CITATION

Rajarajeswari, M.E. and K. Thanushkodi. 2008. "A High Performance DC-DC Converter with Battery Charging Circuit". *Pacific Journal of Science and Technology*. 9(2):309-316.

Pacific Journal of Science and Technology