

Design of PI and Fuzzy Controller for High-Efficiency and Tightly Regulated Full Bridge DC-DC Converter

Sudha Bansal, Lalit Mohan Saini, Dheeraj Joshi

Abstract—The controller is used to improve the dynamic performance of DC-DC converter by achieving a robust output voltage against load disturbances. This paper presents the performance of PI and Fuzzy controller for a phase- shifted zero-voltage switched full-bridge PWM (ZVS FB- PWM) converters with a closed loop control. The proposed converter is regulated with minimum overshoot and good stability. In this paper phase-shift control method is used as an effective tool to reduce switching losses and duty cycle losses. A 1kW/100KHz dc/dc converter is simulated and analyzed using MATLAB. The circuit is simulated for static and dynamic load (DC motor). It has been observed that performance of converter with fuzzy controller is better than that of PI controller. An efficiency comparison of the converter with a reported topology has also been carried out.

Keywords—Full-bridge converter, phase-shifted, synchronous rectifier (SR), zero-voltage switching (ZVS).

I. INTRODUCTION

DC-DC conversion technology has been developing very rapidly, and DC-DC converters have been widely used in industrial applications such as dc motor drives, computer systems and communication equipments. The output voltage of pulse width modulation (PWM) based DC-DC converters can be controlled by changing the duty cycle. In general, to minimize the size and weight of pulse width modulated (PWM) converters, it is required that the switching frequency must be increased. However, increasing the switching frequency leads to substantial switching losses, which causes deterioration in system efficiency. Therefore, the switching losses should be reduced in the case of high switching frequency operation. Various types of resonant converters have been reported to decrease the switching losses during the transient states [1]-[6]. Recently, numerous soft switching techniques for the switching power converters have been proposed [7]-[12]. These techniques reduce the switching losses, thus enabling high frequency operation and also reduce the overall system size. The features of soft switching converters are:

- The resonant network can be composed either of only passive elements and/or it can also have additional auxiliary diode(s) and/or switch (es).
- A high-frequency resonant network is added to the conventional hard-switching PWM dc/dc converters.

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- The soft switching PWM converter is the combination of converter topologies and switching strategies that result in zero-voltage and/or zero-current switching
- These soft-switched converters have switching waveforms similar to those of conventional PWM converters except that the rising and falling edges of the waveforms are 'smoothed' and no transient spikes exist.
- The resonant network is activated only during the switching transition intervals so as to create zero voltage switching (ZVS) and zero current switching (ZCS) conditions.

Soft-switching conditions are:

- Resonance circulating energy be as minimum as possible,
- It is completely decoupled from the main power transfer to the load,
- It should be enough to create the soft-switching conditions, irrespective of the variations in the load, and
- When switching transition is completed, the converter should revert back to the familiar PWM mode of operation, so that the circulatory energy can be minimized.

Among many new techniques [13-16] proposed for high frequency power conversion to reduce the switching loss in traditional PWM converters, the phase- shifted zero-voltage full-bridge pulse width modulation (ZVS FB- PWM) converters are most desirable since they reduce switching loss considerably without the penalty of a significant increase in conduction loss [17]-[20]. Furthermore, the converter operates with a fixed frequency, enabling the design optimization of the circuit with little trouble. The FB ZVS phase-shift DC-DC converter is preferred due to its remarkable features as below:

- It uses the resonance between the switch capacitor and transformer leakage inductor to achieve the zero-voltage switching (ZVS) of the primary switches without the additional resonant components in order to eliminate the switching losses.
- Switches in one leg of the FB inverter conduct with a phase delay with respect to the switches in the other leg. The leg which conducts first is called leading leg and the phase-shifted (PS) leg is called the lagging leg.

It combines the advantages of quasi-resonant converters in respect to the turn on switching losses, and also the advantages of classical PWM converters related to conduction losses and operating frequency. These benefits can be summarized as: ZVS for all the bridge transistors, Reduction of the conduction losses as compared with quasi-resonant converters, Reduction of the electromagnetic noise, Utilization of the device output

capacitance and transformer leakage inductance, Fixed-frequency operation.

However, there are some drawbacks as high circulating currents, loss of duty cycle, ZVS is lost for light loads i.e. narrow ZVS range and load-dependent dc characteristics, also, it undergoes various influences by ringing between the parasitic capacitor of rectifying diodes and the leakage inductance, which cause switching losses and switching noise.

For power levels up to 3 kW, the full-bridge converters employ MOSFET switches and use Phase-Shift Modulation (PSM) to regulate the output voltage. In most of these converters, zero voltage switching (ZVS) is achieved by placing a snubber capacitor across each of the switches and either by inserting an inductor in series with the transformer or by inserting an inductor in parallel to the power transformer [21]-[22]. In a practical full-bridge configuration, the snubber capacitor may be the internal drain-to-source capacitor of the MOSFET, the series inductor may be the leakage inductor and the parallel inductor may be the magnetizing inductor of the power transformer [23]-[25]. This makes the power circuit of these converters very simple.

This paper presents phase-shift control method as an effective tool to reduce switching losses and duty cycle losses. The PI controller and fuzzy controller are used to improve the performance of the soft switched full bridge converter. The phase shift of the secondary active rectifier is controlled by the controllers are designed under the worst case condition of maximum load and minimum line condition. As power electronic converters are nonlinear, and also are prone to variations in its operating states over a wide range, the controllers are to be designed to provide optimal performance as the operating point changes. Simulation of converter subjected to load changes is performed to demonstrate the effectiveness of the proposed controllers. In this paper the operation of full bridge phase-shifted converter and then state space analysis of the converter is discussed in Chapter II. The simulation of converter with PI and fuzzy controllers are performed in the MATLAB/ Simulink to analyze the performance at different loading condition (static and dc motor load). An efficiency comparison of the converter with a reported topology has also been carried out and is shown in Fig. 11.

II. ANALYSIS OF CONVERTER CIRCUIT AND ITS OPERATION

A. Circuit Description

The circuit consists of FB phase-shifted ZVS DC/DC converter and their switching waveforms are shown in Fig. 1. In this conventional full-bridge inverter circuit is connected to the primary of the transformer, and two active switches are connected in the secondary of the transformer forming a synchronous rectifier. These two active switches are phase-shifted with the switches of inverter circuit i.e. the leg with two active switches at the output bridge is phase-shifted from the input bridge. ZVS for these switches can be achieved in the whole load range. Due to the influence of inductor L_k , the reverse recovery currents of diodes in the rectifier are reduced

dramatically. The inclusion of secondary-side switching achieves load independent ZVS range by utilizing the energy stored in the isolation transformer's magnetizing inductance.

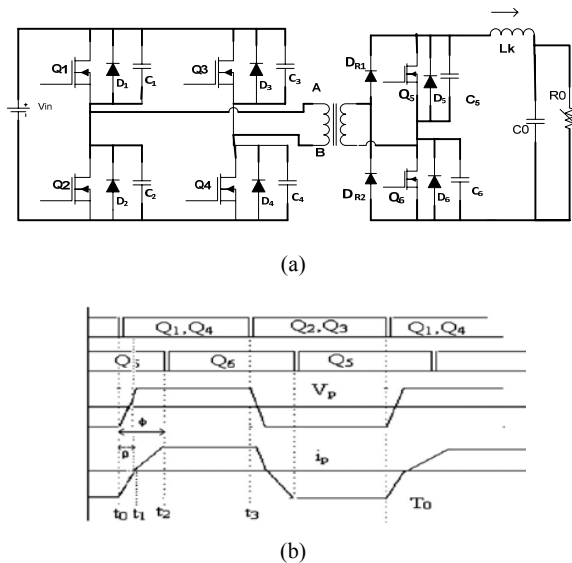


Fig. 1 (a) FB phase-shifted ZVS DC/DC converter and (b) its switching waveform

This secondary-side switching concept is used to control the output bus voltage, resulting in a considerable simplification in the methods used to maintain control and isolation of the DC bus. Furthermore, the maximum reverse recovery voltage will not exceed the output voltage. Here ϕ , is the phase shift given to the control pulse of secondary side w.r.t primary switch, is the phase angle of voltage current waveform, V_p and i_p are the high frequency A.C. voltage and current in the primary of the transformer respectively.

B. Equivalent Circuits

As stated previously, the circuit operation seen from the secondary side has three distinct modes when the converter is in continuous conduction mode (CCM) [27]. Specifically in these three modes, the output stage sees, respectively: (i) a negative input voltage when both Q_1 and Q_4 are on in the primary side, and DR_2 and Q_5 are conducting; (ii) voltage supplied by the filter capacitor when Q_5 still turns on, the secondary side of the transformer is shorted through Q_5 and DR_1 ; and (iii) a positive input voltage across R_0 in the rest of the switching cycle.

Transformer turns ratio is assumed as unity for convenience in the discussion initially. The equivalent circuit for different modes is shown in Figs. 2 (a)-(c).

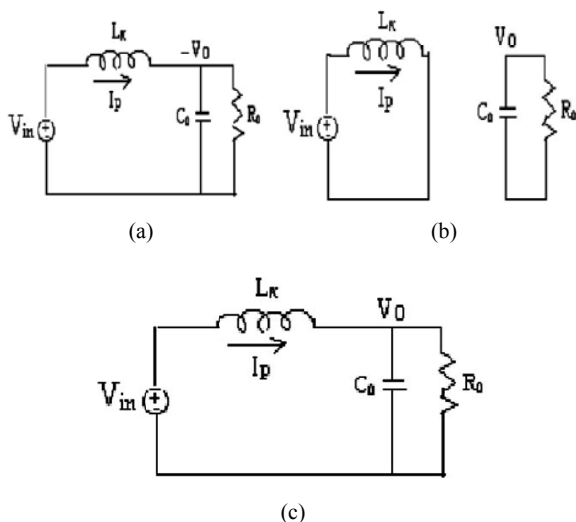


Fig. 2 Equivalent circuits in three different modes of each switching cycle (a) CCM Mode 1 (t_0-t_1) (b) CCM Mode 2 (t_1-t_2) & DCM Mode 1 (t_1-t_2) (c) CCM Mode 3 (t_2-t_3) & DCM Mode 2 (t_2-t_3)

Here V_{in} is the dc input voltage, V_o & R_o is the output voltage and load respectively, C_o is the filter capacitor, L_k is the transformer leakage inductance.

C. State Space Equations

State space equations are derived on the basis of the equivalent circuit for different modes.

1. Mode I

The period of this mode is β (t_2-t_1). In this mode, both Q_1 and Q_4 are on in the primary side, and DR_2 and Q_5 are conducting in the secondary of the transformer. Hence, power is transferred to the load via DR_2 and Q_5 . Then, the network equation for the circuit shown in Fig. 2 (a) will be:

$$L_k \frac{di_p}{dt} = V_o + V_{in} \quad \text{and} \quad C_o \frac{dV_o}{dt} = -i_p + \frac{V_o}{R_o} \quad (1)$$

Thus the state space equations for this mode are obtained as follows:

$$\begin{bmatrix} \frac{di_p}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{L_k} \\ -\frac{1}{C_o} & \frac{1}{R_o C_o} \end{bmatrix} \begin{bmatrix} i_p \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L_k} \\ 0 \end{bmatrix} V_{in} \quad (2)$$

2. Mode 2

The period of this mode is $\Phi - \beta$. When i_p reaches zero, DR_2 and DR_1 commute naturally, so that the soft commutation of the diodes is achieved. As Q_5 still turns on, the secondary side of the transformer is shorted through Q_5 and DR_1 , as shown in Fig. 2 (b), and the input voltage directly applied on inductor L_k and i_p increases linearly. In this period, no power is transferred from input to the load. Thus, the state space equations for this mode are defined by:

$$\begin{bmatrix} \frac{di_p}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{R_o C_o} \end{bmatrix} \begin{bmatrix} i_p \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L_k} \\ 0 \end{bmatrix} V_{in} \quad (3)$$

3. Mode 3

The period of this mode (as shown in Fig. 2 (c)) is $\pi - \Phi$. At t_2 , Q_5 turns off and Q_6 turns on at ZVS condition. The input power is delivered to the output via inductor L_k . The state space equations for this mode can be expressed as:

$$\begin{bmatrix} \frac{di_p}{dt} \\ \frac{dV_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_k} \\ \frac{1}{C_o} & \frac{1}{R_o C_o} \end{bmatrix} \begin{bmatrix} i_p \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L_k} \\ 0 \end{bmatrix} V_{in} \quad (4)$$

Hence the AC model is obtained as:

$$L_k \frac{d\tilde{i}_p}{dt} = \tilde{v}_p \cdot (\beta - \pi + \phi + \tilde{\phi}) + \pi \cdot \tilde{v}_{in} \quad (5)$$

&

$$C_o \cdot \frac{d\tilde{v}_o}{dt} = -I_p \tilde{\phi} + \tilde{i}_p \cdot (-\beta + \pi - \phi) - \frac{\pi}{R_o} \cdot (\tilde{v}_o) - \tilde{i}_p \cdot \tilde{\phi} \cdot \tilde{\phi} \quad (6)$$

On solving above equation, the overall transfer function is calculated as [27]:

$$\frac{\tilde{v}_o(s)}{\tilde{v}_{EA}(s)} = V_o \cdot \frac{R_o}{[k^2 L_k C_o s^2 + (-\beta + \pi - \phi)^2]} \quad (7)$$

III. PI CONTROLLER DESIGN

In order to design a PI controller, the linearized model of the converter has to be determined. Small signal analysis of the PSFB has been made in section II and overall transfer function of the system is determined. The voltage controlled closed loop system is generated. In this, the output voltage is compared with the reference to generate the error signal and this signal is given to the PI controller [28], [29] to obtain the desired phase-shift for the secondary rectifier side active switches. These switches are given phase - shifted pulse to control the output voltage. The block diagram of PI controller is shown in Fig. 3. Output voltage is measured by the voltage sensor and compared with the reference in the comparator. This output of PI controller creates the desired shift in the control pulses given to the switches of inverter and that of rectifier switches.

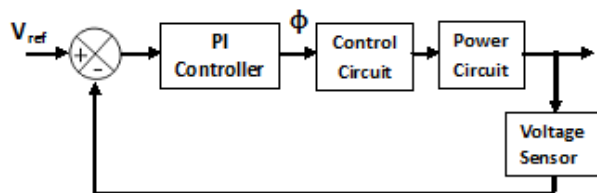


Fig. 3 Voltage controlled PI controller

For the linear controller design, the converter mathematical model must be evaluated. The design of the PI controller poles and zeros are based on the converter frequency response. The value of coefficients of PI Controller depends on the transfer function of the system. The initial values of proportional controller, k_p and integral controller, k_i are taken as 0.1 and 20 and are finely tuned thereafter.

IV. FUZZY LOGIC CONTROLLER DESIGN

PI controller is simple to implement and easy to design, but its performance generally depend on the working point, so that the presence of parasitic elements, time-varying loads and variable supply voltages can make selection of the control parameters difficult, which ensure a proper behavior in any operating conditions. Achieving large-signal stability often calls for a reduction of the useful bandwidth, so affecting converter performance. Fuzzy control is applied to control dc-dc converters because of its simplicity, ease of design and ease of implementation. Fuzzy controllers are well suited to nonlinear time-variant systems and do not need an exact mathematical model for the system being controlled. The fuzzy logic controller determines the operating condition from the measured values and selects the appropriate control actions using the rule base created from the expert knowledge.

Other advantages of FLC are: 1) It can work with less precise inputs; 2) it doesn't need fast processors; 3) it needs less data storage in the form of membership functions and rules than conventional look up table for nonlinear controllers; and 4) it is more robust than other nonlinear controllers.

The fuzzy controller provides a signal proportional to the converter duty-cycle, which is then applied to a standard PWM modulator. The control will work based on two input sets: the output voltage error ($e(k) = V_{ref} - V_{dc}(k)$) and the change in error variations ($de(k) = e(k) - e(k-1)$) which are sampled every $T_{sv} = 5\mu s$. The k is the actual sampling sequence. The basic control structure is shown in Fig. 4.

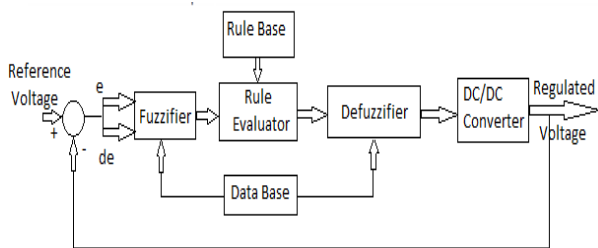


Fig. 4 Internal structure of FLC and closed-loop control of Converter

The FLC has three functional blocks for calculation and two databases. The functional blocks in FLC are: 1) fuzzifier; 2) rule evaluator; and 3) defuzzifier. The two databases are Rule base and Database. Fuzzy logic uses linguistic variables instead of numerical variables. The process of converting a numerical variable (real number) into a linguistic variable (fuzzy number) is called fuzzification. The membership function for error, change in error and output is shown in Fig. 5.

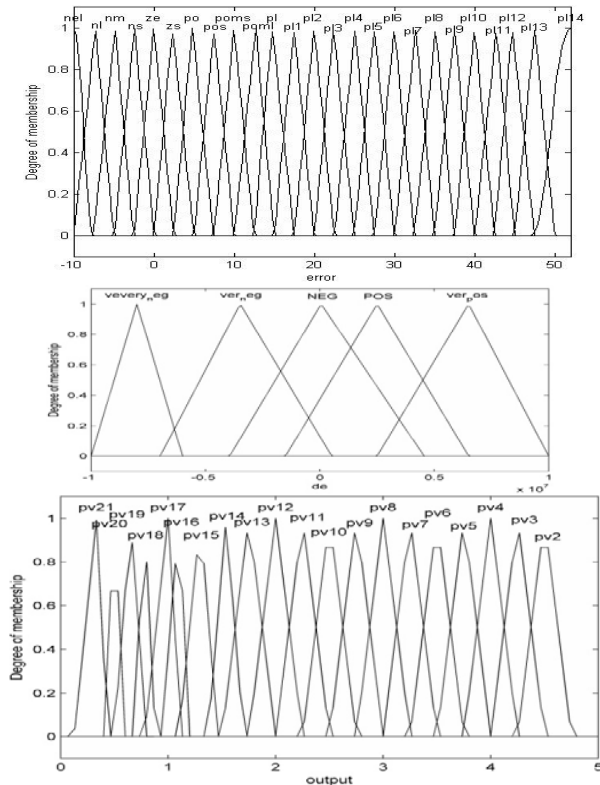


Fig. 5 Membership function plot for error, change in error and output

For a given crisp input, fuzzifier finds the degree of membership in every linguistic variable. Since, there are only two overlapping memberships in this specific case, all linguistic variables except two will have zero membership. In FLC, the equivalent term is rules and they are linguistic in nature. A fuzzy logic controller so designed is used to control the converter by sending the desired control signal to the PWM signal generator.

V. RESULTS AND DISCUSSION

The simulation of the 500 Watt, 100/50 Volt, 100 kHz full bridge phase- shifted DC/DC converter circuit is carried out in MATLAB/ SIMULINK. The values for different circuit parameters are as below:

- Input voltage: 100 Volt
- Output voltage: 50 Volt
- Filter capacitor: 1000 μF
- Load : a) Static load : R-L type load,
- b) Dynamic load : DC motor

In this converter circuit MOSFET Q_5 and Q_6 are given phase shift. This angle is decided by closed – loop control scheme as shown in Fig. 3. The Phase –shifted gate pulses of 100 kHz are produced by comparing saw-tooth waveform with the PI controller output. Control pulses given to various switches are shown in Fig. 6.

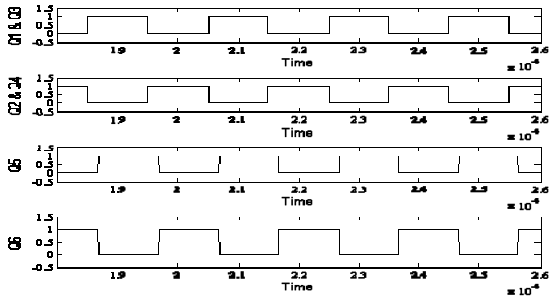


Fig. 6 Phase –shifted Gate pulses

The current and voltage at the output of the inverter circuit is shown in Fig. 7. The converter circuit is simulated under various load conditions. The values of output voltage at different loading condition are taken.

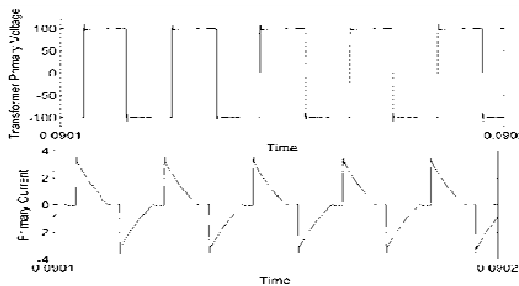


Fig. 7 Transformer voltage and current waveform at the primary of the Inverter

A. Static Load

1. With PI Controller

The converter’s performance is tested at 10% of full -load to 20% of full -load in the case: load is reduced to 10% of full-load, at $t = 0.06$ sec and load is increased to 20% at $t = 0.1$ sec. Output voltage and current are shown in Fig. 8 (a).

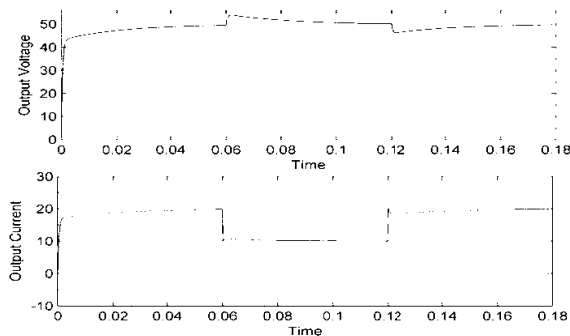


Fig. 8 (a) Output Voltage and Current of the DC/DC converter at 20% of load, when sudden load is reduced to 10% of full load at $t=0.06$ sec, with PI controller

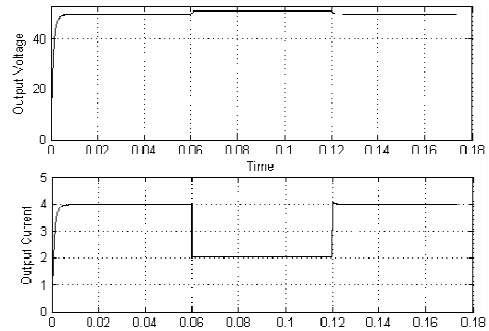


Fig. 8 (b) Output Voltage and Current of the DC/DC converter at 40% of load, When Sudden load is reduced to 20% of full load at $t = 0.06$ sec, with fuzzy controller

2. With Fuzzy Controller

The converter’s performance is tested at 10% of full - load to 20% of full -load in the case. Load is reduced to 10% of load, at $t = 0.06$ sec and load is increased to 20% at $t = 0.1$ sec. Output voltage and current are shown in Fig. 8 (b).

3 At Full Load and 50% of Load

The converter’s performance is tested at full load and 50% of load in the case: (a) when load is reduced to 50% of load, at $t = 0.06$ sec and load is increased to full load at $t = 0.12$ sec. (b) Again load is reduced to half load at $t = 0.18$ sec and load is increased to full load at $t = 0.24$ sec.

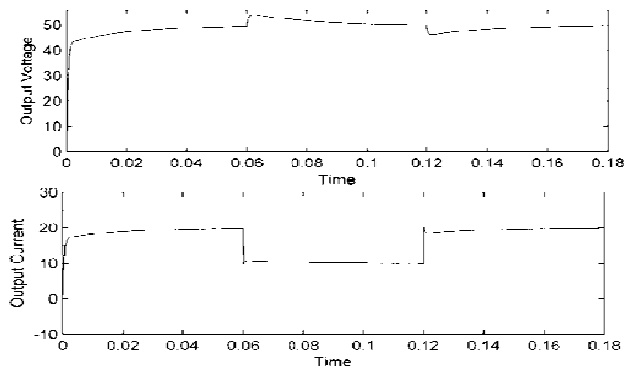


Fig. 9 Output Voltage and Current of the DC/DC converter at 100% load, When Sudden load is reduced to 50% load at $t=0.06$ sec & again increased at $t=0.12$ sec

B. Dynamic Load

A 1.3 h.p. DC motor load is powered by the converter and regulation of the converter output voltage is maintained with the same PI controller, output voltage and current at different loading conditions are shown in Figs. 10 (a) and (b).

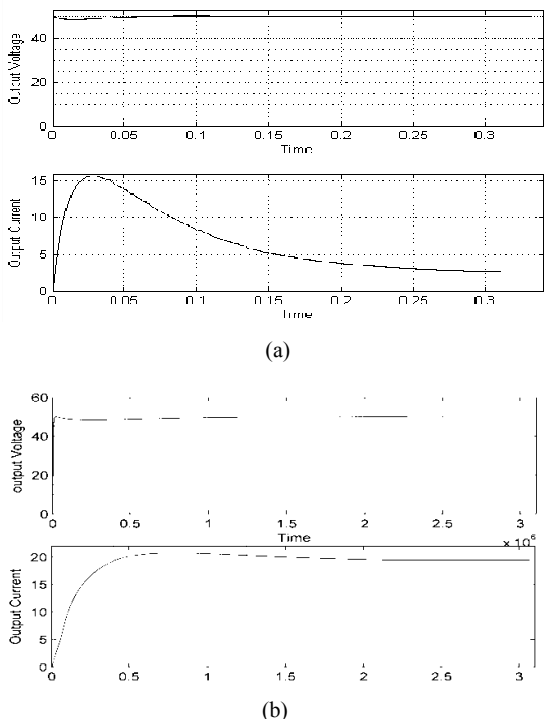


Fig. 10 (a) Output Voltage and Current of the DC/DC converter at 10% of DC Motor load (b) Output Voltage and Current of the DC/DC converter at 100% of DC Motor load

The performance of converter is checked by simulation of the circuit with these controllers from MATLAB/SIMULINK. The results of output voltage and current are shown in Fig. 8. The results obtained from the circuit simulation with static and dynamic load at various load conditions with PI Controller taken at different values of k_p and k_i are summarized in Tables I and II. We can see that with different value of k_p and k_i , peak overshoot, settling time and steady state error changes. The optimum value of k_p and k_i are obtained as 0.1 & 17 respectively and the steady state error observed in the range of 0- 0.3 % for variation of the load from 5% of load to full – load. It is less than the specified limit of 0.5%.

TABLE I
% STEADY STATE ERROR= 0.50% (SPECIFIED)
PERFORMANCE MEASURES OF CONVERTER WITH STATIC LOAD (WITH PI CONTROLLER)

S. No	% of full-load	k_p	k_i	Peak overshoot (%)	Settling time (Sec)	% Steady state error
1	83.3	0.1	17	0	0.06	0.3
2	62.5	0.1	17	0	0.05	0.1
3	40	0.1	15	0	0.06	0.04
4	40	0.08	20	1.2	0.04	0.03
5	40	0.08	17	0.4	0.035	0.06
6	40	0.1	17	0.2	0.03	0.04
7	20	0.1	17	2.4	0.04	0.3
8	10	0.1	17	4	0.06	0.24
9	10	0.1	15	3.4	0.08	0.3
10	5	0.1	17	3.6	0.07	0.3

TABLE II
% STEADY STATE ERROR= 0.50% (SPECIFIED)
PERFORMANCE MEASURES OF CONVERTER WITH DC MOTOR (DYNAMIC) LOAD (WITH PI CONTROLLER)

S. No.	% of full-load	k_p	k_i	Peak overshoot (%)	Settling time (Sec)	% Steady state error
1	20%	0.1	17	2.4	0.05	0.02
2	40%	0.1	17	0.6	0.05	0.02
3	60%	0.1	17	0.4	0.05	0.02
4	80%	0.1	17	0.4	0.05	0.02
5	100%	0.1	17	0.4	0.05	0.02

The similar results with fuzzy controller are tabulated in Table III. On comparison with both types of controllers in Table IV, it is observed that performance with fuzzy controller is better than PI controller.

TABLE III
% STEADY STATE ERROR= 0.50% (SPECIFIED)
PERFORMANCE MEASURES OF CONVERTER WITH FUZZY CONTROLLER

S. No	% of full-load	Peak overshoot (%)	Settling time (Sec)	% Steady state error
1	20%	1.1	0.02	0.02
2	40%	1.1	0.02	0.02
3	60%	1.2	0.02	0.02
4	80%	1.2	0.02	0.02

TABLE IV
PERFORMANCE COMPARISON OF PI AND FUZZY CONTROLLER

Type of controller	Peak overshoot	Settling time (Sec)	% Steady state error
PI controller	0- 3.6	0- 0.08	0- 0.3
Fuzzy controller	1.1 - 1.2	0.02	0.02

The efficiency of the converter with different loading is also taken. The results so obtained is compared with the topology reported in [26] in Fig. 11.

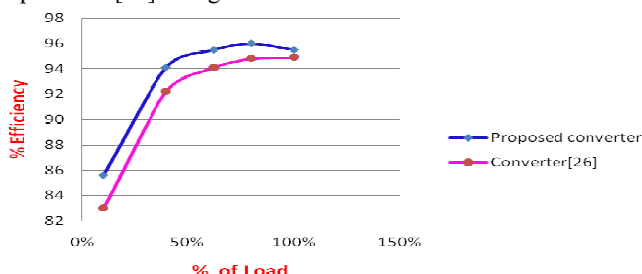


Fig. 11 Efficiency at different load

VI. CONCLUSION

This paper has presented two different controllers PI and fuzzy controller to improve the dynamic response of the DC/DC boost converter against the load variation. It has been observed that the system is stable from 5% of load to full load. The system shows excellent performance when DC motor load is applied. The system is also verified on frequent change of load. The simulation result shows that the performance of converter with fuzzy controller ensures the tight regulation of output voltage effectively under the load uncertainty. The efficiency of the converter at different loading conditions is

also measured and improvement in efficiency is found. The average efficiency obtained is approx. 95.6%.

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