INVESTIGATIONS ON FUZZY CONTROLLED INTERLEAVED BUCK CONVERTER FED PMBLDC DRIVE SYSTEM

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ABSTRACT

Permanent Magnet Brushless DC Motor (PMBLDC) is one of the best electrical drives that has increasing popularity, due to their high efficiency, reliability, good dynamic response and very low maintenance. Its predominant applications are in automotive, aerospace, household appliances, office automation and other industries. This paper proposes a new multistage interleaved buck converter fed PMBLDC drive system having very low switching losses and improved step down conversion ratio, which is suitable for the applications where the input voltage is high and the output voltage is low, where the operating duty cycle is below 50%. When compared with the conventional interleaved buck converter where two active switches are connected in series and a coupling capacitor is connected in the power path, where as in the proposed Multistage Interleaved Buck Converter (MIBC) fed system it can be seen that the voltage stress across all active switches is half of the input voltage before turn on or turn-off when the operating duty cycle is below 50%, the capacitive discharging and switching losses can be reduced considerably, following that the MOSFET fed inverter bridge is feeding the PMBLDC drive system. This allows the proposed multistage IBC to have higher efficiency and operate with higher switching frequency. In addition, the proposed Multistage IBC has a higher step-down conversion ratio and a smaller output current ripple compared with a conventional IBC. The multistage IBC fed PMBLDC drive system features, operation principles, relevant analysis and results are presented in this paper. The validity of this study is confirmed by the experimental results of prototype system with 40-60V Input, 12V/5A output. Further the closed loop system is controlled using Fuzzy controller to enhance the motor performance in various load conditions and the corresponding results are also presented.

Keywords: buck converter, multistage interleaved, low switching losses, conversion ratio, PMBLDC motor, closed loop, fuzzy controller.

INTRODUCTION

Permanent magnet brushless DC motor a BLDC motor is defined as a type of self-synchronous rotary motor controlled by electronic commutation, where the rotor is a permanent magnet with rotor-position sensors (R.Krishnan, 2003). And corresponding commutation circuit could be either independent or integrated to the motor. A BLDC motor is considered here as trapezoidal motor with the starting characteristics of series excitation DC motors and the speed-regulation characteristics of shunt excitation DC motors (Chang-Liang Xia, 2012). It has advantages like simple structure, high efficiency and large torque, etc. Hence, it is widely used in national defense, aerospace, robotics, industrial process control, precision machine tools, automotive electronics, household appliances and office automation. (S.Prakash *et al*., 2013) The continual development of BLDC applications makes it more interesting towards the associated design and analysis for various applications (S.Prakash *et al*., 2013). This in turn controls the motor for all its defined applications with high efficiency, as well as good in maintaining the speed for variable torque.

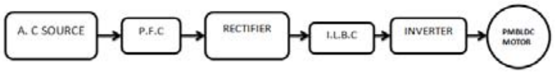

Figure-1. Structure of MILBC fed PMBLDC drive system.

The structure of the PMBLDC motor drive system as shown in Figure-1has an A.C. source, where the A.C. supply is fed to the rectifier circuit through the power factor correction block where it has L & C elements used for Power factor correction. Then rectifier is used to convert the available A.C. source in to D.C. source and then it is fed to the Multi Stage Interleaved Buck Converter where depending upon the motor need, a constant input voltage is provided and then it is connected with the inverter and finally supply is fed to the PMBLDC motor.

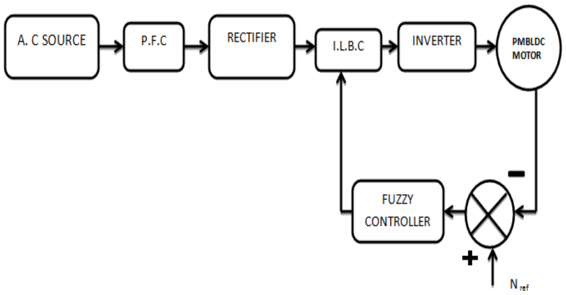

Figure-2. Structure of MILBC fed PMBLDC drive system in closed loop.

The structure of the closed loop PMBLDC motor drive system is shown in Figure-2 where the fuzzy logic controller has been introduced in order to feed the motor with a constant input voltage, whatever may be the load condition. By using the fuzzy controller the speed is controlled.

A REVIEW ON MULTISTAGE INTERLEAVED BUCK CONVERTER

While designing the motor drives the following techniques have to be considered so as to design a flexible lossless system. In desired applications, where we need no isolation, step-down conversion ratio, and high output current with low ripple are required, Interleaved buck converter are preferred because of its simple structure and low control complexity. In ordinary IBC it has high cost, high on-resistance, high forward voltage drop, severe reverse recovery; it operates under hard switching condition, so efficiency becomes poor. For high power density and better dynamics, it is required that converter should operate at higher switching frequencies (S.Prakash *et al.* 2014). But switches and switching losses will be increased while turn-on, turn-off and reverse recovery. To overcome the drawbacks, continuous research has been made for reducing the voltage stress of a buck converter. In the proposed technology that is by using Multi Stage Interleaved Buck Converter, the voltage stress is half of the input voltage in converters. The voltage across all semiconductor devices can be reduced by adjusting the turns ratio of the coupled inductors. Here, a single capacitor turn off snubber is used. Its advantages are that the switching losses are reduced (Rahul Khopkar *et al.* 2003). It leads to discontinuous conduction mode (DCM), so that the switches are pushed to very high current stress. IBC's with ZVS were also practiced(Il-Oun Lee *et al.* 2012). This creates high conversion ratio and stress voltage level across the freewheeling diodes can be reduced. But to have the advantages, it requires additional elements and active switches, which increases the cost. IBC with Zero Current Transition (ZCT) is introduced to reduce diode reverse recovery losses. An IBC with Multistage as shown in Figure-1, has parallel connected coupled inductors which has the following advantages, lower input and output ripple, reduced capacitor current leads to less expensive capacitors, doubling of ripple frequency, (Pushpavalli M. *et al.* 2013) lesser filter components, heat sink requirement is less, improved transient response, reduction in peak currents and Lower EMI Noise generation. The voltage stress is reduced in the semiconductor devices, maintains high power factor (Milan Ilic *et al.* 2007), switching losses are reduced and gives better step down conversion ratio(P. Rameshbabu *et al.* 2013**)**. The above literature does not deal with fuzzy controlled ILBC fed PMBLDC drive. This research work proposes fuzzy controller for ILBC fed PMBLDC drive.

ANALYSIS OF MULTISTAGE I.L.B.C SYSTEM

Figure-3 shows the circuit configuration of the proposed IBC. The structure is similar to a conventional IBC except where we have three active switches in series and a coupling capacitor employed in the power paths. Various modes for each switching period are shown in Figs 2a to 2f. Some assumptions made are as follows:

- Resistance of the choke is neglected;
- Output capacitor Co is large enough to be considered as a voltage source;
- ESR of the capacitor is neglected;
- Devices are assumed to be ideal.

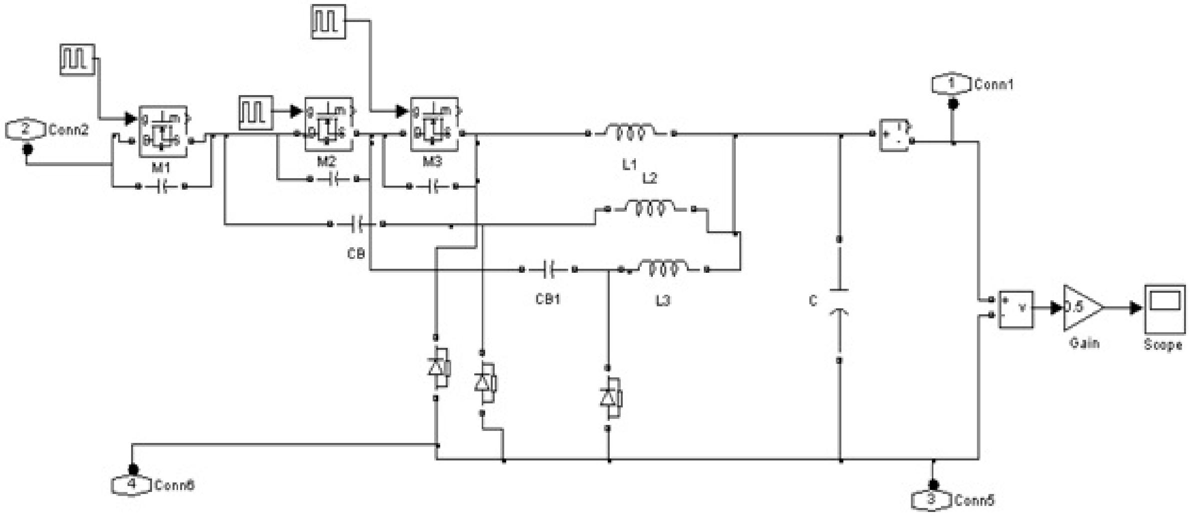

Figure-3. Simulink diagram of multistage interleaved buck converter.

Mode 1

When the switch M1 is closed the current flows through the capacitor CB and L2 and then to the load, as shown in Figure-4 and it also charges the capacitor C. The Mode equations are as follows:

$$E = VCB + VL2 + VO \tag{1}$$

$$\text{Whereas, } VL2 = L2\frac{di}{dt} \tag{2}$$

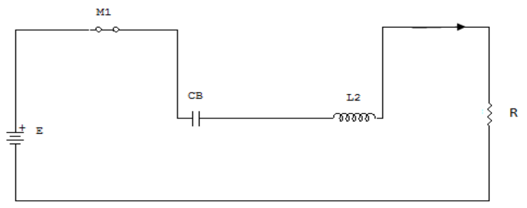

Figure-4. Mode 1.

Mode 2

When the switch M1 is open, L2 and L3 supplies energy to the capacitor C and the load is fed from the filter capacitor. Mode equations are as follows:

$$iL2 + iL3 = iC + iO = iC + \frac{Vo}{R} \tag{3}$$

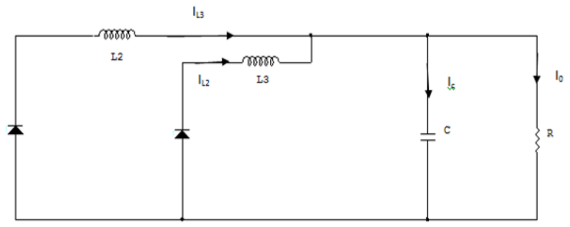

Figure-5. Mode 2.

Mode 3

When the switch M2 is closed, the current passes through capacitor CB1, L3 and then to the load as shown in Figure-6 and capacitor also charges. The mode equations are as follows:

$$E = VC1 + VL3 + VO \tag{4}$$

$$\text{Whereas, } Vc1 = \frac{1}{C1}\int i.dt \tag{5}$$

Figure-6. Mode 3.

Mode 4

When the switch M2 is open, L 2 and L3 are connected to the capacitor c as shown in Figure-7. The mode equations are as follows:

$$VL + VC = 0, \tag{6}$$

$$\text{Whereas, } Vc = Vo \tag{7}$$

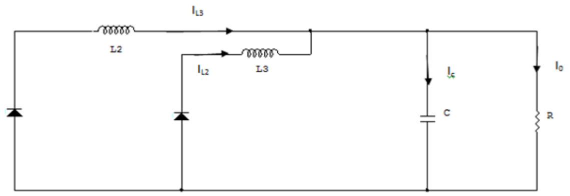

Figure-7. Mode 4.

Mode 5

When the switch M3 is closed then the current passes through C b1 and L3 and then to the load and simultaneously it charges the capacitor c. The mode equations are as follows:

$$E = VC1 + VL3 + VO \tag{8}$$

$$\text{Whereas, } IO = \frac{Vo}{R}$$

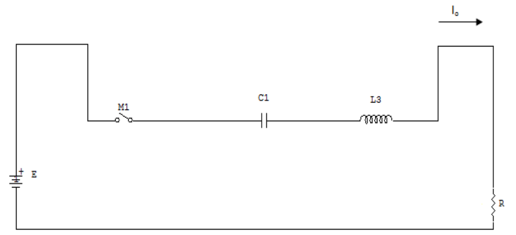

Figure-8. Mode 5.

Mode 6

When the switch M3 is open, L2 and L3 are connected to the capacitor c and the load as shown in Figure-9. The mode equations are as follows:

$$VL2 = L2\frac{di_2}{dt} \tag{9}$$

$$VL3 = L3\frac{di_3}{dt} \tag{10}$$

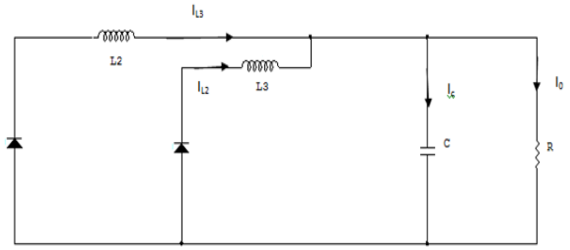

Figure-9. Mode 6.

STRESS CALCULATIONS OR CALCULATION OF STRESS

It is assumed that IBC's should operate with the duty cycle of D≤0.5.

To obtain the stress, the following values are used,

1. Input Voltage : 48 V A.C
2. Output Voltage: 12 V D.C.
3. Switching Frequency : 6.6 kHz
4. Output Current : 1.5 Amps

Results

1. Actual Voltage output : 11.74 Volts
2. Voltage stress across the switches: M1 = 12x103 Volts/Sec, M2 = 15x103 Volts/Sec, M3 = 32x103 Volts/Sec .

Hence it is investigated that due to the improved voltage waveforms in the three stage IBC, the capacitive discharging and switching losses are reduced. Therefore multistage interleaved buck converter is preferred to normal buck converter.

SIMULATION RESULTS

The Interleaved buck converter fed PMBLDC drive system is simulated using Matlab/Simulink. The Simulink model of the interleaved buck converter fed PMBLDC drive is shown in Figure-10. Here 48V DC is given as input then the voltage is stepped down to 24V DC using a buck converter. The output of the buck converter is filtered using L C filter. The output of the filter is applied to the three phase inverter. The inverter produces three phase voltage required by the PMBLDC motor.

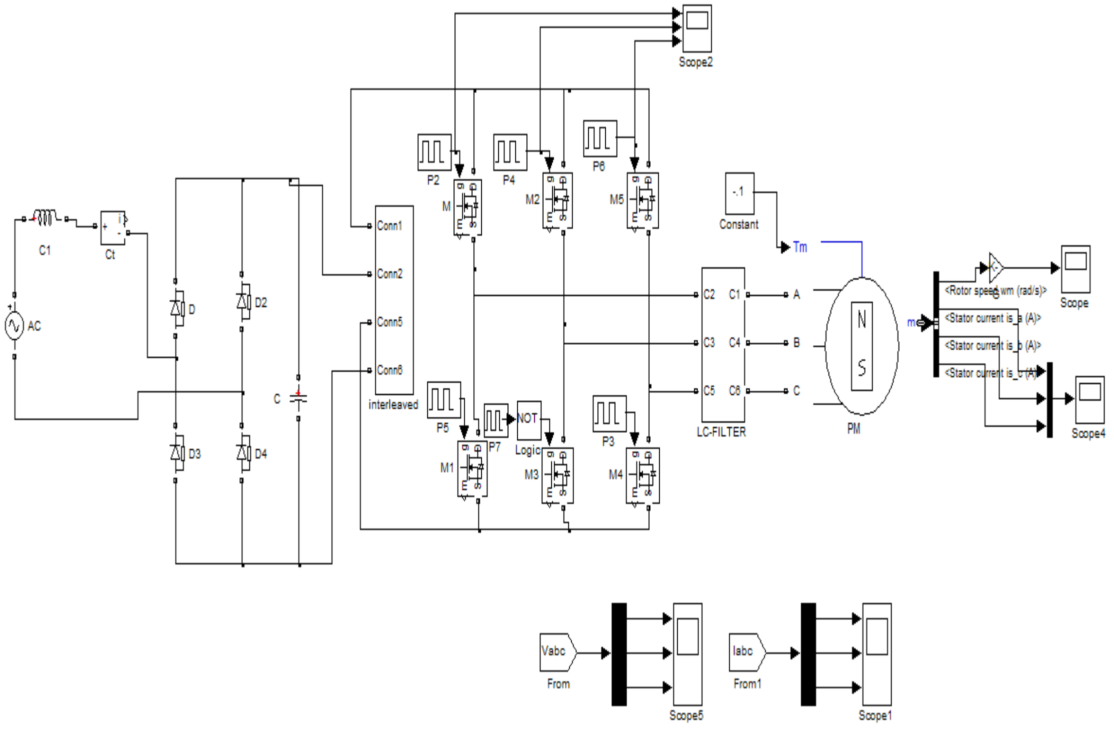

Figure-10. Simulink diagram of interleaved buck converter fed PMBLDC drive system.

The simulink diagram of interleaved buck converter fed PMBLDC drive system is shown where AC voltage is rectified and it is applied to the ILBC. The DC output of ILBC is converted into 3Phase AC using a three phase inverter. The input voltage and current waveforms are shown in Figure-11. The voltage and current are almost in phase due to the power factor correction circuit at the input. The switching pulses for M1, M3 & M5 are shown in Figure-12. The output voltage of ILBC is shown in Figure-13.

The lines to neutral voltages are shown in Figure-14. The speed response of the motor is shown in Figure-15. The speed settles at 270 rpm.

Fuzzy controlled closed loop system is shown in Figure-16. The step change in input voltage is shown in Figure-17 the input voltage increases from 48volts to 53 volts. The speed response is shown in Figure-18. It can be seen that the speed is maintained constant after 0.5 seconds by the fuzzy controller. The response is shown in Figure-19. The developed torque increases and settles in 0.5 seconds. This is due to the increase in the load at 0.5 seconds.

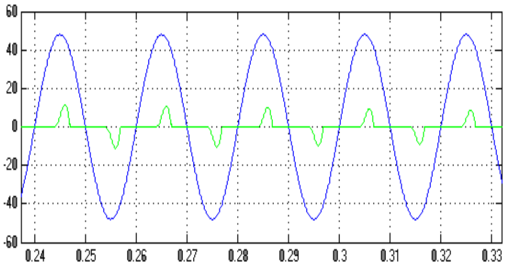

Figure-11. Input voltage and current.

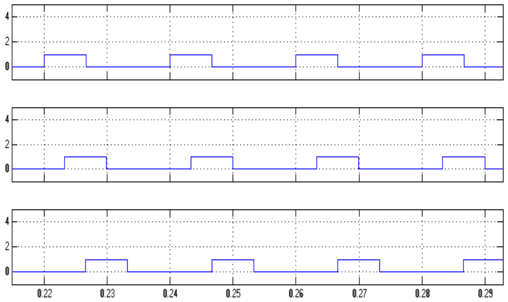

Figure-12. Switching pulse for inverter switches M1, M3 & M5.

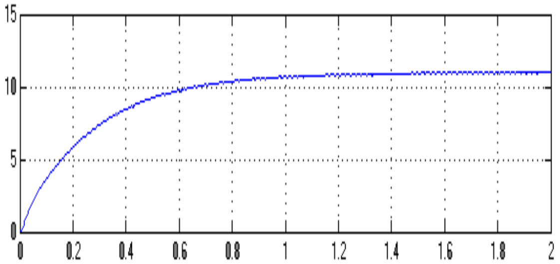

Figure-13. Output voltage of Interleaved Buck Converter.

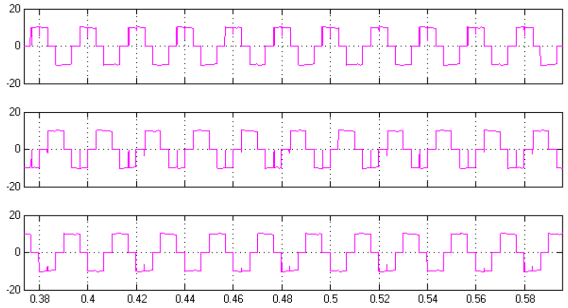

Figure-14. Phase voltage waveforms

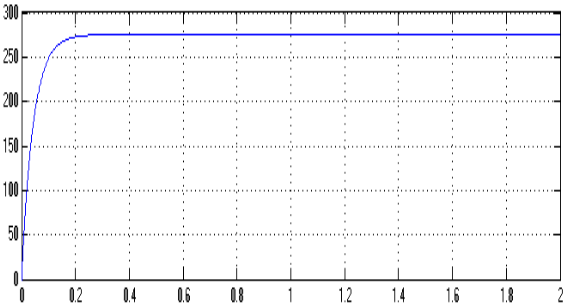

Figure-15. Motor speed.

SIMULATION RESULTS OF CLOSED LOOP WITH FUZZY CONTROLLER

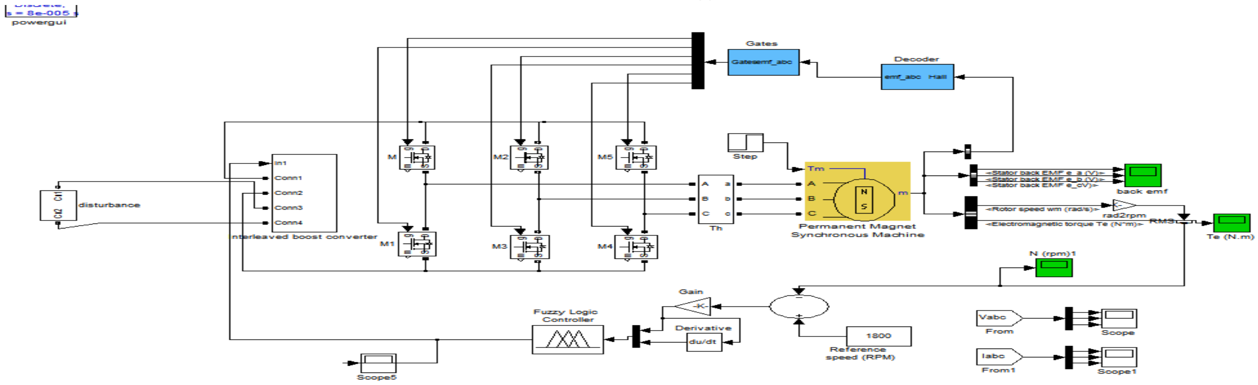

Figure-16. Simulink diagram of fuzzy controller fed closed loop PMBLDC drive system.

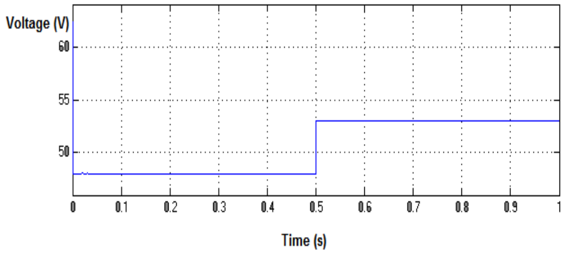

Figure-17. Change in the input voltage.

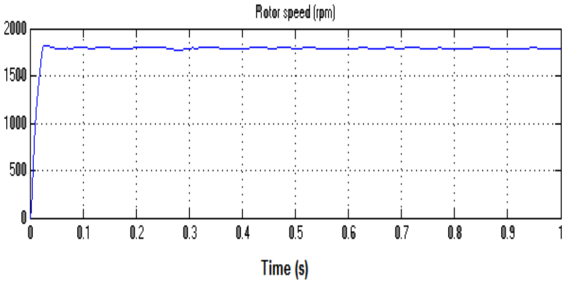

Figure-18. Rotor speed in RPM.

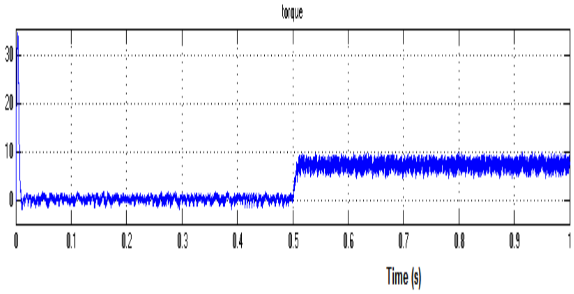

Figure-19. Torque in N.m.

Table-1. Comparison of responses of PID & FLC based systems.

S. No.	Controllers	**Rise time** (Secs)	**Peak time** (Secs)	**Settling time** (Secs)	**Steady state error** (rpm)
1	PID controller	0.04	0.05	0.2	15
2	Fuzzy controller	0.02	0	0.05	2

Comparison of responses of PID & FLC based systems are given in Table-1. The settling time is reduced from 0.2 to 0.05 seconds and the steady state error is reduced from 15 to 2 RPM.

EXPERIMENTAL RESULTS

The hardware is fabricated and tested in the laboratory. The oscillogram of pulses to switch1 is shown in Figure-20. The output voltage of ILBC is shown in Figure-21. The Phase Voltage is shown in Figure-22. The hardware setup is shown in Figure-23. The hardware comprises of control board and power board. It can be seen that the experimental results match with the simulation results.

Figure-20. Pulse to the inverter switch 1.

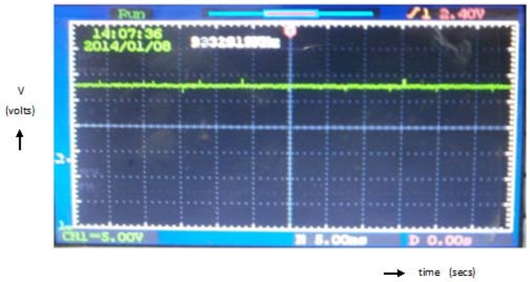

Figure-21. Output voltage of Interleaved Buck Converter.

Figure-22. Line to line voltage.

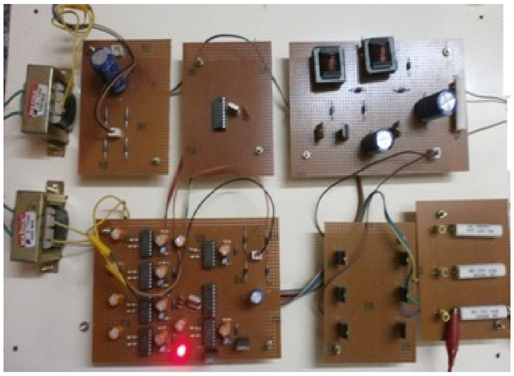

Figure-23. Hardware setup of Interleaved Buck Converter.

CONCLUSIONS

The Multistage Interleaved Buck Converter fed PMBLDC drive system is simulated using MATLAB/SIMULINK. The simulation and hardware results are presented. A Multistage Interleaved Buck Converter is proposed to supply the input voltage to the drive system. The output of the multistage interleaved buck converter depends on the duty cycle. The L-C filter is proposed at the output of the IBC to reduce the ripple. This drive system designed with Multistage ILBC has prime advantages like low voltage stress to switches, good dynamic response and perfect speed performance. The scope of this work is to simulate and make hardware of multistage interleaved buck converter fed PMBLDC drive system. The results are compared and with ordinary buck converter as well as Multistage Interleaved Buck Converter, and it is found that MILBC has superior response and very low loses. A better drive system for PMBLDC motor is realized through this MILBC. The simulation results are in line with the theoretical results and are best compared with Hardware results also. Similarly the complete results of closed loop system with fuzzy controller are also presented. The settling time is reduced by 75% and steady state error is reduced by 13% using FLC. The response with ANN controller will be studied in the future.

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