An FLC based BLDCM Drive with Power Factor Improvement Using Isolated Zeta Converter

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ABSTRACT-This project deals with an Isolated Zeta Converter as a power-factor-correction converter for a permanent magnet (PM) brushless dc motor (PMBLDCM) fed through a diode bridge rectifier from a single-phase ac mains, using Fuzzy Logic Controller. A three-phase voltage-source inverter is used as an electronic commutator to operate the drive. The speed of the motor is controlled by the voltage control at dc link which is proportional to the desired speed of the PMBLDCM. The stator currents of the PMBLDCM during change in the reference speed are controlled within the specified limits of the reference dc link voltage. The proposed PMBLDCM drive (PMBLDCMD) is designed and modeled, and its performance is evaluated in Mat lab–Simulink environment. Simulated results are presented to demonstrate an improved power factor at ac mains of the PMBLDCMD system in a wide range of speed. Test results of a developed controller are also presented to validate the design and model of the drive.

1. INTRODUCTION

Brushless dc (BLDC) motors are becoming popular due to their advantages of high efficiency, high energy density, high torque/inertia ratio, variable speed operation, and low electromagnetic interference (EMI) [1]. They find applications in household appliances, medical equipments, robotics and automation, transportation, and industrial tools. The BLDC motor is a three-phase synchronous motor with three-phase concentrated windings on the stator and permanent magnets on the rotor. It needs a three-phase voltage source inverter (VSI) for achieving an electronic commutation of BLDC motor based on the rotor position as sensed by Hall Effect position sensors.

A diode bridge rectifier (DBR) with a high value of smoothening capacitor is generally used for feeding the BLDC motor. It draws a distorted supply current from ac mains due to uncontrolled charging and discharging of the dc link capacitor [2]. Such type of supply current is highly distorted in nature and has a very high total harmonic distortion (THD) in the order of 65%–70% which further leads to a poor factor (PF) in the order of 0.7–0.72 at ac mains. Such power quality indices are not acceptable within the limits of international power quality standards such as IEC 61000-3-2 [3]. Another major problem in such drive is the cost of current sensors required for achieving the pulse width modulation (PWM)-based current control of BLDC motor for speed control. This suffers from high switching losses in three-phase VSI due to high frequency switching of PWM signals. Such losses are reduced by operating the VSI in fundamental frequency switching by electronically commutating the BLDC motor. Moreover, the speed is controlled by varying the dc link voltage of VSI. This reduces the switching losses of VSI and eliminates the requirement of current sensors for PWM-based current control of BLDC motor for speed control.

Power factor correction (PFC) converters are widely used for improving the power quality at ac mains. Various configurations of nonisolated and isolated PFC converter have been reported in the literature for improving the power quality at ac mains. The cost of these PFC converters is primarily decided by the sensing requirements which in turn depend upon the mode of operation of the PFC converter. Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are two modes of operation of a PFC converter. PFC converter operating in CCM offers low stress on PFC converter switches but requires sensing of supply voltage, dc link voltage, and supply current, which is a costly option in terms of cost of sensors. However, PFC converter operating in DCM requires single voltage sensor for dc link voltage control, and inherent PFC is achieved at ac mains but at the cost of high stress on PFC converter switches.

Therefore, this mode of operation is limited to low-power applications. A boost-PFC converter has been widely used for feeding the BLDC motor drive for power quality improvements at ac mains .A constant dc link voltage is maintained at the dc link capacitor of VSI, and PWM-based switching is used for the speed control of BLDC motor. This offers high switching losses in the VSI due to high switching frequency of PWM signals and high cost associated due to a large number of sensors. Some configuration of a PFC-based BLDC motor drive using a single-phase PFC converter has been reported. A PFC-based Cuk converter feeding BLDC motor has been proposed in.

This configuration uses a variable voltage control of VSI for speed control of BLDC motor, and hence operates the VSI in fundamental switching frequency for reduced switching losses. But, a CCM mode of operation of PFC Cuk converter is used, which requires three sensors for voltage control with PFC at ac mains. This configuration is mainly suited for high-power applications. Nonisolated bridgeless converters have been proposed in for feeding BLDC motor but have high number of component count. Moreover, these configurations cannot be used in many applications requiring a galvanic isolation for safety issues.

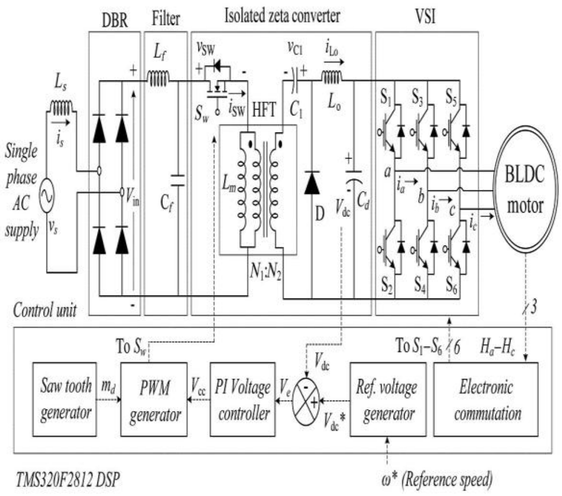


Fig. 1. Proposed PFC-based isolated zeta converter fed BLDC motor drive.

II .Proposed PFC-Based BLDC Motor Drive With High-Frequency Isolation

Fig.1 shows the proposed PFC-isolated zeta converter-fed BLDC motor drive. A single-phase supply is used to feed a DBR followed by a filter and an isolated zeta converter. The filter is designed to avoid any switching ripple in the DBR and the supply system. An isolated zeta converter is designed to operate in DCM to act as an inherent power factor corrector. This combination of DBR and PFC converter is used to feed a BLDC motor drive via a three-phase VSI as shown in Fig.1. The dc link voltage of the VSI is controlled by varying the duty ratio of the PWM pulses of PFC converter switch. However, VSI is operated in a low frequency switching to achieve an electronic commutation of BLDC motor for reduced switching losses. A single voltage sensor is used at the front-end converter for the control of dc link voltage for speed control of BLDC motor. The proposed drive is designed and its performance is validated on a developed prototype for improved power quality at ac mains for a wide range of speed control and supply voltage variations. Specifications of the BLDC motor selected for experimental studies are given in Appendix.

III OPERATION OF ISOLATED PFC ZETA CONVERTER

The operation of an isolated zeta converter is classified into three different modes corresponding to switch turn-ON, switch turn-OFF, and DCM. Three modes are shown in Fig.2(a)–(c) and their associated waveforms are shown in Fig.3. These modes are described as follows.

Mode I: When switch (Sw) is turned "ON," a current in magnetizing inductance (Lm) of high frequency transformer (HFT) increases as shown in Fig.2 (a). The intermediate capacitor (C1) supplies energy to an output inductor (Lo) and the dc link capacitor (Cd). Hence, voltage across intermediate capacitor (VC1) reduces, and the current in output inductor (iLo) and dc link voltage (V_{dc}) are increased as shown in Fig.3

Mode II: When switch (Sw) is turned "OFF," the current in magnetizing inductance (Lm) of HFT and output inductor (Lo) starts reducing. This energy of HFT is transferred to the intermediate capacitor (C1), and therefore voltage across it increases. Diode (D) conducts in this mode of operation, and the dc link voltage (Vdc) increases as shown in Fig. 3.3

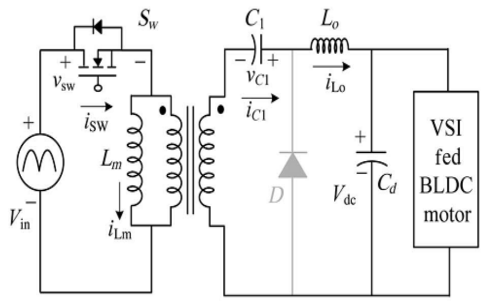
Mode III: This mode is DCM such that the energy of HFT is completely discharged as shown in Fig. 3.2(c). The intermediate capacitor (C1) and the dc link capacitor (Cd) supply the energy to the output inductor (Lo) and the load, respectively. Hence, the dc link voltage (Vdc) and intermediate capacitor's voltage (VC1) are reduced, and the output inductor current increases in this mode of operation as shown in Fig.3

IV DESIGN OF ISOLATED PFC ZETA CONVERTER

An isolated PFC zeta converter is designed to operate in DCM such that the current flowing in magnetizing inductance of HFT (Lm) becomes discontinuous in a switching period. A PFC converter of 300 W (Pmax) is designed for the selected BLDC motor (complete specifications are given in Appendix). For a wide range of speed control, the dc link voltage is controlled from a low value of 50 V (Vdc min) to a rated voltage of 130 V (Vdc max) with supply voltage variation from 170 V (VS min) to 270 V (VS max). The input voltage VS applied to the PFC converter as

$$V_S(t) = V_m \sin(\omega_L t) = 220\sqrt{2}\sin(314t)V \quad (1)$$

where V m is peak input voltage (i.e., √2VS) and ωL = 2πfL; fL is the line frequency, i.e., 50 Hz.



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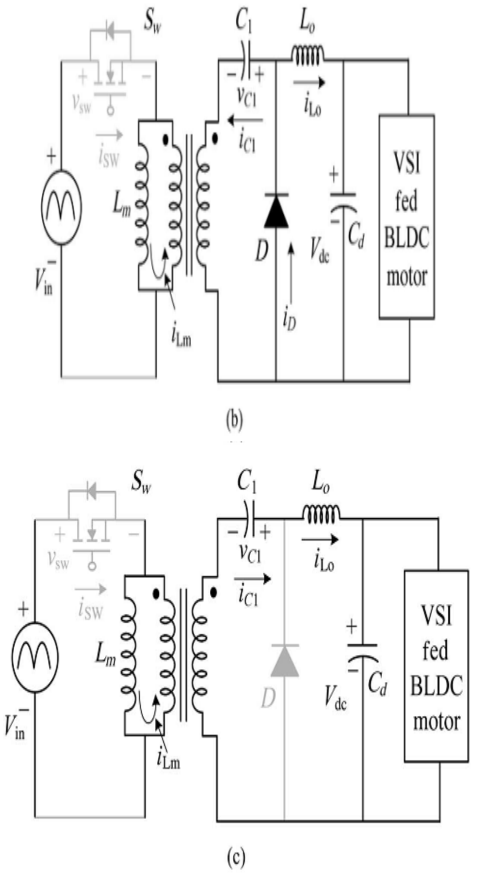

Fig.2. Three modes of operation of an isolated zeta converter.

The instantaneous output voltage of DBR is given as

$$V_{in}(t) = \left|V_m \sin(2\pi f_L t)\right| = \left|220\sqrt{2}\sin(314t)\right| V \quad (2)$$

where represents the modulus function. The output voltage Vdc of an isolated zeta converter which belongs to a buck-boost category is given as [7]

$$V_{dc} = \left(\frac{N_2}{N_1}\right)\frac{D}{(1-D)}V_{in} \quad (3)$$

where D represents the duty ratio and N2/N1 is the turns ratio of the HFT which is taken as 1/2 for this application. The instantaneous value of duty ratio D(t) depends on the input voltage Vin(t) and required dc link voltage Vdc. An instantaneous duty ratio D(t) is obtained by substituting (2) in (3) and rearranging it as

$$D(t) = \frac{V_{dc}}{\left(\frac{N_2}{N_1}\right)V_{in}(t) + V_{dc}} = \frac{V_{dc}}{\left(\frac{N_2}{N_1}\right)\left|V_m \sin(\omega t)\right| + V_{dc}}. \quad (4)$$

Since the speed of the BLDC motor is controlled by varying the dc link voltage of the VSI, therefore, the instantaneous power Pi at any dc link voltage (Vdc) is taken as linear function of Vdc as

$$P_i = \left(\frac{P_{max}}{V_{dc\ max}}\right)V_{dc} \quad (5)$$

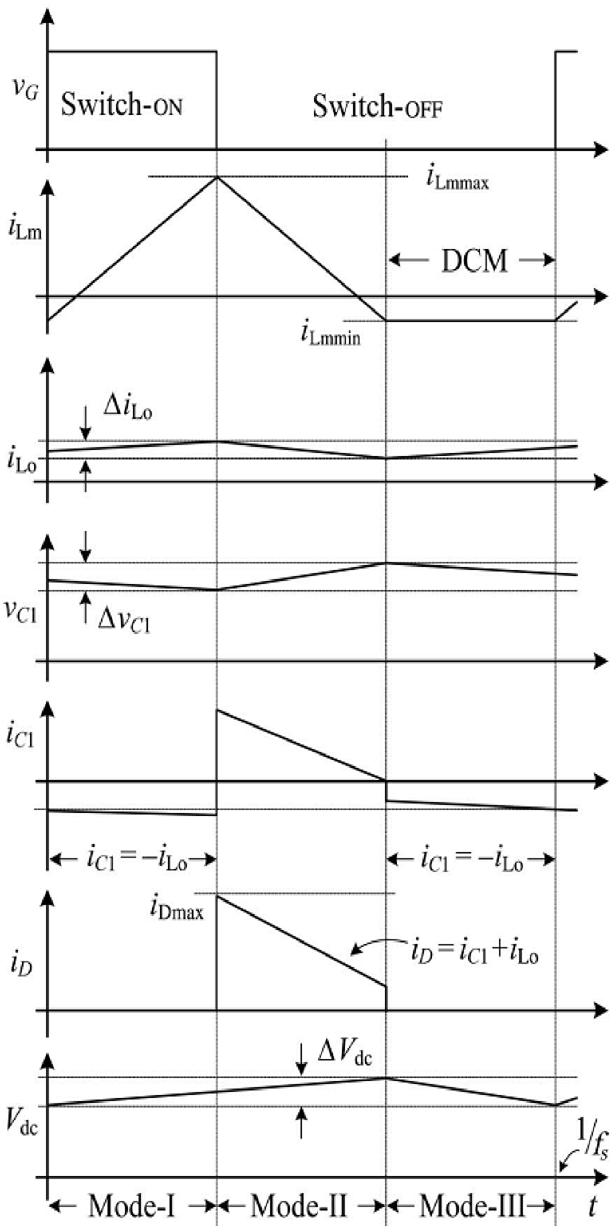

Fig.3. Operating waveforms of an isolated zeta converter.

where Vdc max represents maximum dc link voltage, and Pmax is the rated power of the PFC converter. Using (5), the minimum power (P_{min}) corresponding to the minimum dc link voltage (Vdc min) is calculated as 115 W. The critical value of magnetizing inductance of the HFT (Lmc) is expressed as [13]

$$L_{mc} = \frac{R_L\{1-D(t)\}^2}{2D(t)f_S(N_2/N_1)^2} = \left(\frac{V_{dc}^2}{P_i}\right)\frac{\{1-D(t)\}^2}{2D(t)f_S(N_2/N_1)^2} \quad (6)$$

where RL represents the emulated load resistance, f_s is the switching frequency (which is taken as 20 kHz), and Pi is the instantaneous power. The critical value of magnetizing inductance (Lmc) is calculated for maximum current corresponding to lowest possible value of supply voltage, i.e., 170 V.

V.CONTROL OF ISOLATED PFC ZETA CONVERTER-FED BLDC MOTOR DRIVE

PFC-based BLDC motor drive is divided into two categories: control of PFC converter for dc link voltage control and control of three-phase VSI for electronic commutation of BLDC motor.

1. Control of Front-End PFC Converter

A voltage-follower approach is used for the control of isolated zeta converter operating in DCM. This control scheme consists of a reference voltage generator, voltage error generator, voltage controller, and a PWM generator. A "reference voltage generator" generates a reference voltage Vdc ∗ by multiplying the reference speed (ω∗) with the motor's voltage constant (kv) as

$$V_{dc}^* = k_v \omega^*. \quad (16)$$

The "voltage error generator" compares this reference dc link voltage (Vdc ∗) with the sensed dc link voltage (Vdc) to generate an error voltage (V_e) given as

$$V_e(k) = V_{dc}(k)^* - V_{dc}(k) \quad (17)$$

where "k" represents the kth sampling instance. This error voltage Ve is given to a voltage PI (proportional integral) controller to generate a controlled output voltage (Vcc) which is expressed as

$$V_{cc}(k) = V_{cc}(k-1) + K_p\{V_e(k) - V_e(k-1)\} + K_i V_e(k) \quad (18)$$

where Kp and Ki are the proportional and integral gains of the PI controller (values are given in Appendix). Finally, the PWM signal for switch Sw is generated by comparing the output of PI controller (Vcc) with high-frequency
saw-tooth signal (md) given as

$$\left\{ \begin{array}{l} \text{if } m_d < V_{cc}, \text{ then } S_w = \text{“ON”} \\ \text{if } m_d > V_{cc}, \text{ then } S_w = \text{“OFF”} \end{array} \right\} \quad (19)$$

where Sw represents the gate signal to PFC converter switch. A rate limiter is also introduced for limiting the stator currents of the BLDC motor during step change in dc link voltage for speed control. This rate limiter limits the rate of change of duty ratio of PWM pulses which is to be given to the PFC converter switch. The rising and falling slew rates of the rate limiter
are selected to limit the peak current within twice the rated current of BLDC motor.

2. Control of BLDC Motor

An electronic commutation of BLDC motor includes proper switching of VSI in such a way that a symmetrical dc current is drawn from the dc link for 120◦ and placed symmetrically at the centre of back-EMF of each phase . A Hall effect position sensor is used to sense the rotor position on a span of 60◦; which is required for the electronic commutation of BLDC motor. As shown in Fig.1, when two switches of VSI, i.e., S1 and S4 are in conduction states, a line current iab is drawn from the dc link capacitor whose magnitude depends on applied dc link voltage (Vdc), back EMF's (ean and ebn), resistances (Ra and Rb), and self and mutual inductance (La, Lb, and M) of stator windings [18]. This current produces the electromagnetic torque (Te) which in turn increases the speed of the BLDC motor.

VI.INTRODUCTION TO FUZZY LOGIC CONTROLLER

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to dc-to-dc converter system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of dc-to-dc converter and performance of proposed controllers. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of dc-to-dc converters. The basic scheme of a fuzzy logic controller is shown in Fig 5 and consists of four principal components such as: a fuzzification interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

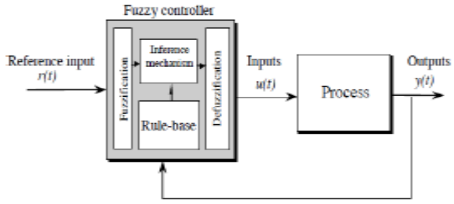

Fig.4. General Structure of the fuzzy logic controller on closed-loop system

The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model [10]. Simulation is performed in buck converter to verify the proposed fuzzy logic controllers.

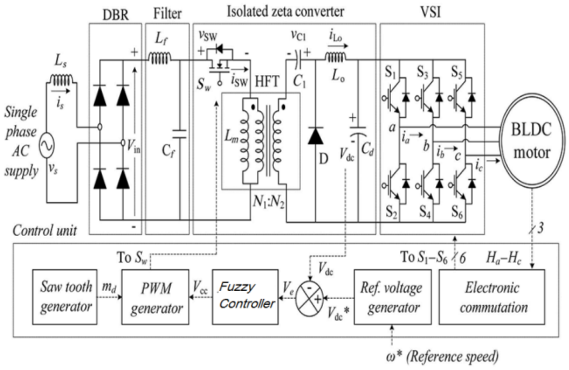

Fig.5. Block diagram using Fuzzy Logic Controller (FLC)

A. *Fuzzy Logic Membership Functions:*

The dc-dc converter is a nonlinear function of the duty cycle because of the small signal model and its control method was applied to the control of boost converters. Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying operating points. Fuzzy Logic Controller is designed to control the output of boost dc-dc converter using Mamdani style fuzzy inference system. Two input variables, error (e) and change of error (de) are used in this fuzzy logic system. The single output variable (u) is duty cycle of PWM output.

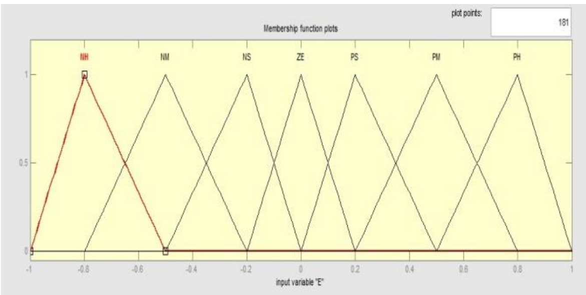

Fig. 6.The Membership Function plots of error

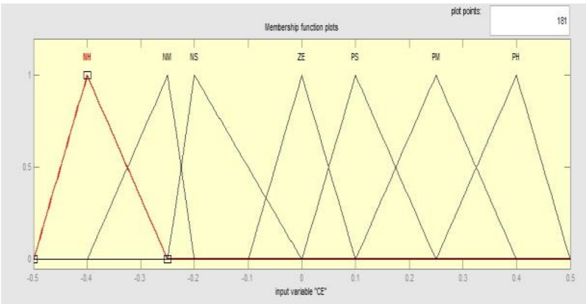

Fig.7. The Membership Function plots of change error

B. *Fuzzy Logic Rules:*

The objective of this dissertation is to control the output voltage of the boost converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into seven groups; NB: Negative Big, NM: Negative Medium NS: Negative Small, ZO: Zero Area, PS: Positive small, PM: Positive Medium and PB: Positive Big and its parameter [10]. These fuzzy control rules for error and change of error can be referred in the table that is shown in Table I as per below:

Table I
Table rules for error and change of error

e/ce	NB	NM	NS	ZO	PS	PS	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

VII. MATLAB/SIMULINK RESULTS

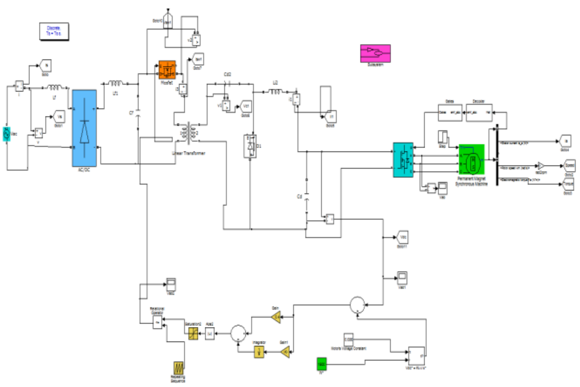

Fig. 8 shows the matlab/Simulink model of proposed system with PI controller

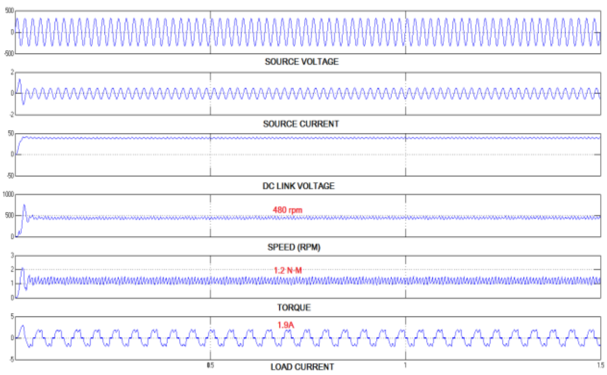

Fig.9 shows the performance of the isolated zeta converter based BLDC motor with PI controller at full load condition

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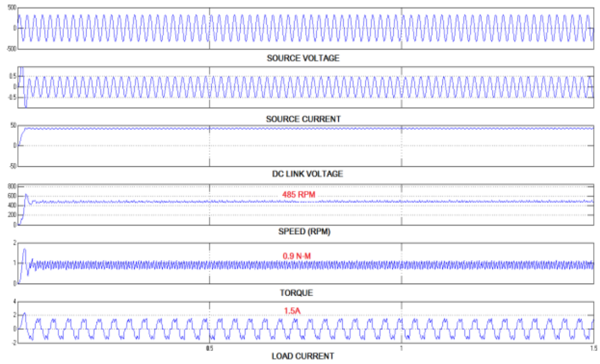

Fig.10 shows the performance of the isolated zeta converter based BLDC motor with PI controller at 3/4th load condition

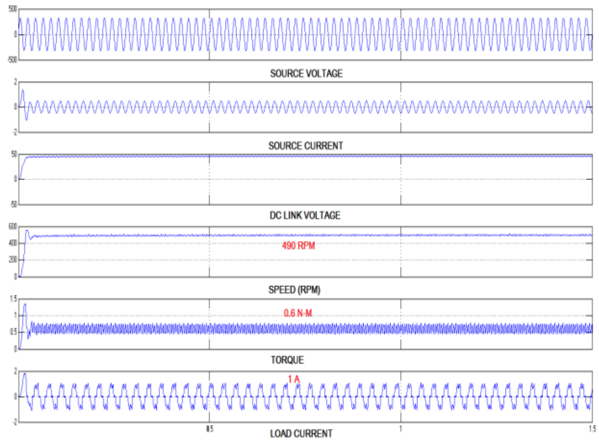

Fig.11 shows the performance of the isolated zeta converter based BLDC motor with PI controller at half load condition

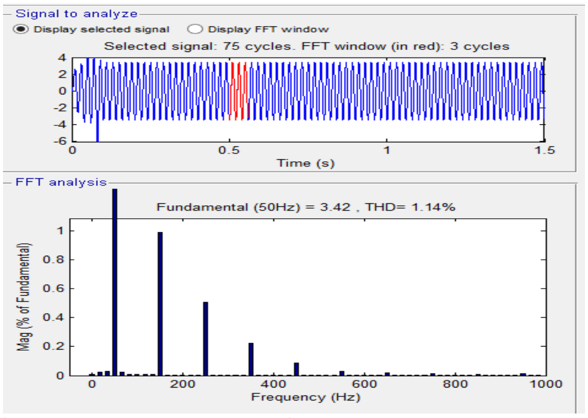

fig.12 shows the THD response of source current with PI controller

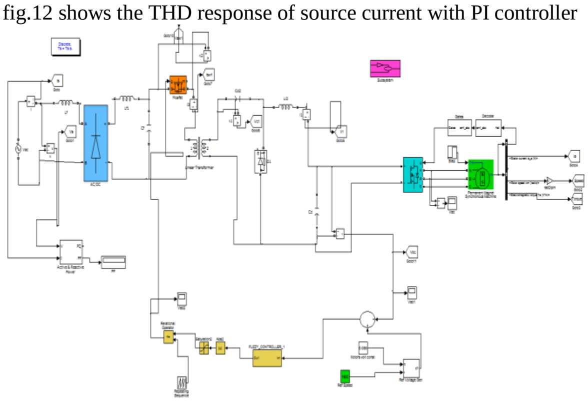

Fig. 13 shows the matlab/Simulink model of proposed system with fuzzy logic controller

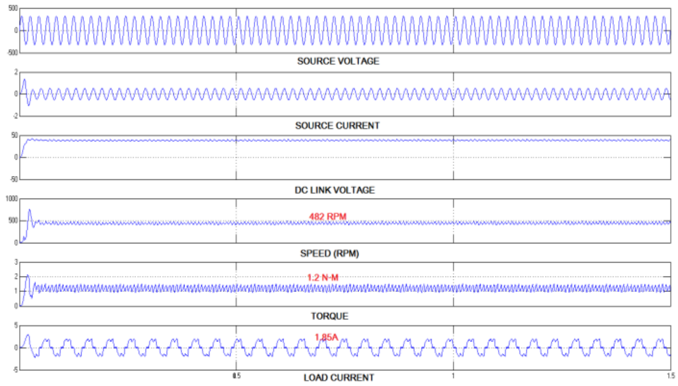

Fig.14 shows the performance of the isolated zeta converter based BLDC motor with fuzzy logic controller at full load condition

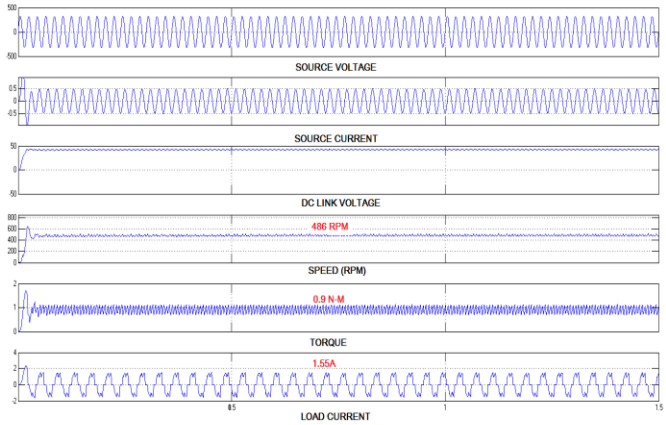

Fig.15 shows the performance of the isolated zeta converter based BLDC motor with fuzzy logic controller at 3/4th load condition

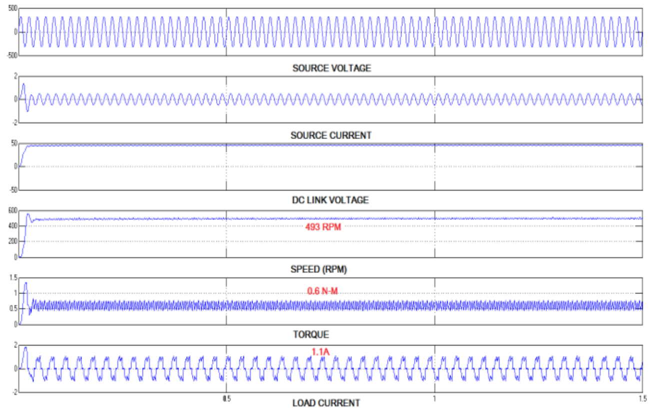

Fig.16 shows the performance of the isolated zeta converter based BLDC motor with fuzzy logic controller at half load condition

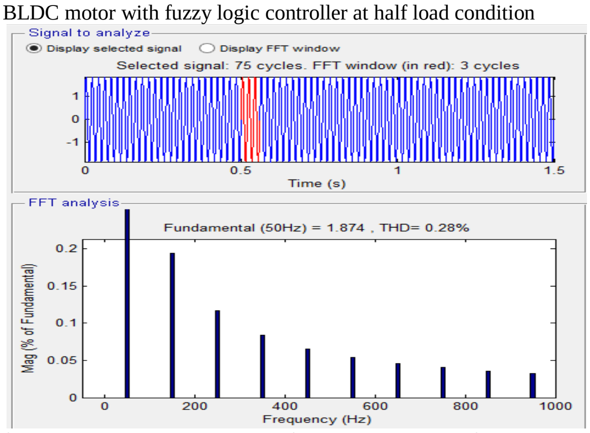

fig.17 shows the THD response of source current with fuzzy logic controller

% load	% THD		Power factor	
	With PI	With Fuzzy	With PI	With Fuzzy
Full load	1.14	0.28	0.954	0.9809
3/4TH Load	1.1	0.26	0.959	0.9880
½ Load	1.05	0.25	0.969	0.9903

Table 2 : Comparison of PF between PI and FLC Controllers

VII. CONCLUSION

An isolated zeta converter-fed BLDC motor drive has been proposed for targeting low-power household appliances. A variable dc link voltage of VSI feeding BLDC motor has been used for controlling the speed. With this PFC converter, three-phase VSI has been operated in low frequency switching mode with reduced switching losses. A front-end isolated zeta converter operating in DCM has been used for dc link voltage control and with PFC at ac mains. Performance of proposed drive has been found quite satisfactory for speed control over a wide range. A prototype of proposed drive has been implemented with satisfactory test results for its operation over complete speed range and its operation at wide range of supply voltages. The obtained power quality indices have been found within the limits of IEC 61000-3-2.

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