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Zeta Converter Fed Brushless DC Motor Drive for Power Factor Correction in Low Power Applications

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ABSTRACT

This paper proposes a zeta converter fed brushless dc (BLDC) motor with power factor correction (PFC). The zeta converter uses a high-frequency transformer and operates in Discontinuous conduction mode (DCM). The speed variation in the BLDC motor is achieved by varying the DC link voltage. The DC link voltage is calculated corresponding to the duty cycle of the converter switch. The proposed drive is realized as an efficient method for power factor correction in low-power applications.

Keywords: Discontinuous Conduction Mode (DCM), Continuous Conduction Mode (CCM), Zeta Converter, Brushless DC (BLDC) Motor, Power Factor Correction (PFC), Voltage Source Inverter (VSI).

I. INTRODUCTION

Brushless DC motors (BLDC) are gaining recognition due to their wide range of industrial and commercial applications such as automotive, health sector, and aerospace. They dominate in household appliances like fans, hairdryers, robotic vacuum cleaners, coffee machines, air-conditioners, pump etc [1]. They have high efficiency due to better electro-mechanical energy conversion. These results in a remarkable reduction in the power required for its operation. Also, BLDC motors are popular because of its variable speed control, bi-directional operation and quick response [2]. The stator of BLDC motor has three windings connected in a star arrangement. The rotor is made of permanent magnets that give low rotor inertia. Due to low rotor inertia dynamic performance of the drive is good. A BLDC motor also operates at high speed as they do not any have mechanical restrictions like brushes and commutator. The lack of commutator reduces complexity and maintenance.

For the efficient operation of BLDC motor, the stator windings must be energised in a proper sequence. Hence, excitation of the rotor is based on the rotor position data which is fed back to the VSI. Rotor position data is obtained by using rotor position sensors. Once the knowledge of this sequence is acquired, the stator windings can be energised correspondingly [3]. Generally, BLDC motor is fed by an A.C supply via a diode bridge rectifier (DBR), DC link capacitor and a voltage source inverter (VSI). But this configuration gives poor power factor and increased harmonics at A.C mains. Hence the usage of power factor correction (PFC) topologies is highly recommended for such drives [4-5].

Few converter configurations for correcting power factor are Flyback [15], Sepic [17], Cuk [13] and Zeta [19]. These converters fall under Buck-Boost [16] category implicating that they can either step up or step down the input voltage based on their requirements [6]. Zeta converter is a fourth order converter that uses less number of switches compared to Buck-Boost. Zeta also offers additional safety against over

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current and inrush current as compared to other converter topologies. Hence, in low power applications, zeta converter is more beneficial over other DC-DC converters. A Zeta converter fed BLDC drive is proposed in this paper. The Isolated zeta converter has some advantages including safety at the output region, and flexibility for output adjustment [14].

This paper is split into five sections. The first section gives a brief introduction to BLDC drives. The next section details the working of *Isolated Zeta Converter Fed Brushless DC Drive*. In the third section, the *Operation of Isolated Zeta Converter* is explained. In the following section, the *Design and Simulation results of Isolated Zeta Converter Fed BLDC Drive* are shown. The last section gives the *Conclusion* drawn from the circuit.

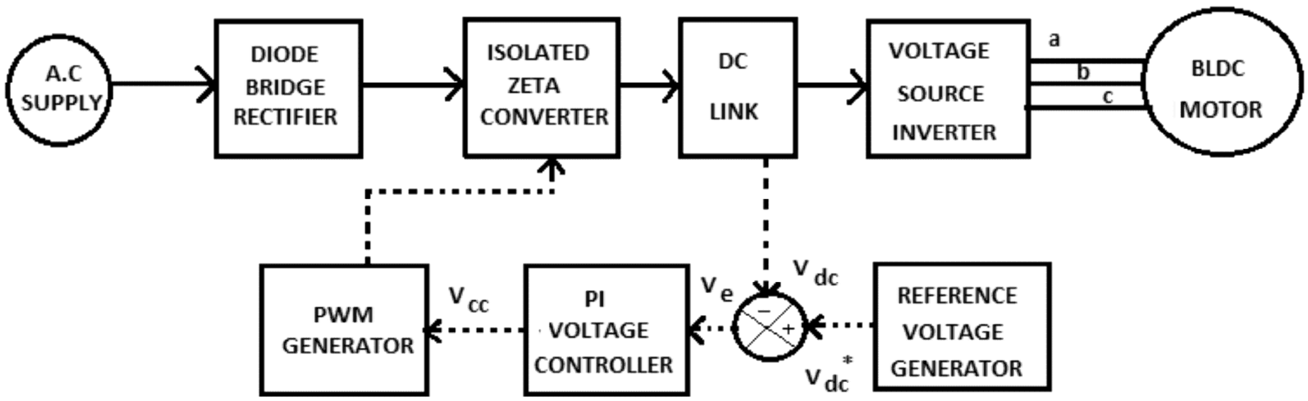

Figure 1: Isolated zeta converter fed BLDC drive

II. ISOLATED ZETA CONVERTER FED BRUSHLESS DC DRIVE

The Diode bridge rectifier and zeta converter are connected to the BLDC motor drive through a three-phase VSI. A PFC converter operates in Continuous Conduction Mode (CCM) or in Discontinuous Conduction Mode (DCM). This paper uses DCM mode of zeta converter. In CCM, the inductor current stays continuous for a switching period, but in DCM it becomes discontinuous. CCM mode requires the current multiplier control and two voltage sensors while DCM mode requires only a single voltage sensor for controlling DC link voltage. CCM operation causes low current stress on zeta converter switch while the current stress is more in DCM. Hence DCM operation of zeta converter is chosen only for low-power applications [18]. The speed control of BLDC motor is achieved by controlling the DC link voltage. The DC link voltage of the VSI can be controlled by altering the duty ratio of converter switch. A single voltage sensor used in the front end converter measures the voltage at the DC link. The output of DC link is then supplied as input to the VSI, which is switched at low frequency to attain electronic commutation of BLDC motor [8].

III. OPERATION OF ISOLATED ZETA CONVERTER

The isolated zeta converter has three modes of operation : switch turn-ON, switch turn-OFF, and DCM. Three modes are explained in detail below.

Mode I: When the switch (S_w) is turned “ON,” the current in magnetizing inductance (L_m) of high frequency transformer (HFT) increases. An intermediate capacitor (C_1) supplies energy to the output inductor (L_o) and DC link capacitor (C_d). Hence, voltage across the intermediate capacitor (V_{c1}) reduces, and the current in output inductor (i_{Lo}) and DC link voltage (V_{dc}) are increased.

Mode II: When the switch (S_w) is turned “OFF,” a current in magnetizing inductance (L_m) of HFT and output inductor (L_o) starts reducing. The energy of HFT is transferred to the intermediate capacitor (C_1), increasing its voltage. The diode (*D*) conducts and the DC link voltage (V_{dc}) increases.

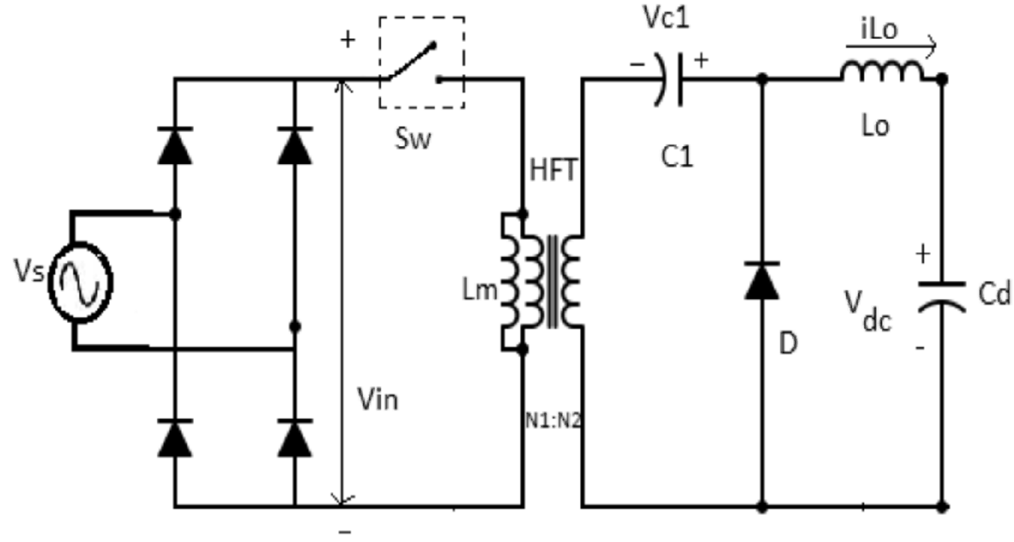

Figure 2: Isolated zeta converter operation

Mode III: This mode is DCM such that the energy of HFT is completely discharged. The intermediate capacitor (C_1) and the DC link capacitor (C_d) supply the energy to the output inductor (L_o) and the load, respectively. Hence, the DC link voltage (V_{dc}) and intermediate capacitor (V_{c1}) are reduced, and the output inductor current increases in this mode of operation.

IV. DESIGN OF ISOLATED ZETA CONVERTER

An isolated zeta converter operating in DCM is designed for dc link voltage ranging from 50V ($V_{dc, min}$) to 130V ($V_{dc, max}$) and supply voltage ranging from 170V ($V_{s, min}$) to 270V ($V_{s, max}$).The design specifications are as follows.

P_o (Output power) = 300W, V_s (Supply voltage) = 220V, V_{dc} (DC link voltage) = 130 V, f_L (Line frequency) = 50 Hz, Δi_{Lo} (Permitted ripple current in inductor L_o) = 10% of I , ΔV_{c1} (Permitted ripple voltage in intermediate capacitor, $C1$) = V_m (Peak of input voltage), ΔV_{dc} (Permitted DC link voltage ripple) = 3% of V_{dc}, f_S = 20kHz, HFT ratio = n:1.

The input voltage applied to PFC converter is,

$$V_s = 220 \text{ V} \tag{1}$$

Where f_L, is the line frequency, 50 Hz.

The output voltage of DBR is given as,

$$V_{in} = 2\, Vm/\pi = 198 \text{ V}. \tag{2}$$

The DC link output voltage V_{dc} of an isolated zeta converter which belongs to a buck-boost category is given as [5]

$$V_{dc} = \left(\frac{N2}{N1}\right)\frac{D}{1-D} V_{in} = 99 \text{ V}. \tag{3}$$

Where *D* is the duty ratio and *N*2/*N*1 is the turn's ratio of the HFT, which is taken as 1/2 for this application.

An instantaneous duty ratio *D*(*t*) depends on the DC link output value. *D*(*t*) is obtained by substituting (2) in (3) and rearranging it as

$$D(t) = \frac{V_{dc}}{V_{dc} + \left(\frac{N2}{N1}\right) V_{in}(t)} = 0.50 \tag{4}$$

The speed of the BLDC motor is varied by controlling the dc link voltage of the VSI. Therefore, the instantaneous power P_i at any dc link voltage is taken as linear function of V_{dc} given by

$$P_i = \frac{P_{max}}{V_{dc,max}} V_{dc} = 115W \tag{5}$$

Where $V_{dc, max}$ represents maximum dc link voltage, and P_{max} is the rated power of the PFC converter.

Using (5), the minimum power (P_{min}) corresponding to the minimum dc link voltage ($V_{dc, min}$) is calculated s 115 W.

$$V_{s,min} = 170v,$$

$$D_a(t) = \frac{V_{dc}}{V_{dc} + \left(\frac{N2}{N1}\right) V_{s,min}\sqrt{2}} = 0.5196 \tag{6}$$

$$V_{s, max} = 270v,$$

$$D_b(t) = \frac{V_{dc}}{V_{dc} + \left(\frac{N2}{N1}\right) V_{s, max}\sqrt{2}} = 0.4051$$

The critical value of magnetizing inductance of the HFT (L_{mc}) is expressed as [14]

$$L_{mc} = \frac{V_{dc}{}^2{}_{max}(1 - D_a)^2}{P_{max}(2Dfs)} = 2.52mH \tag{8}$$

Where Da(*t*) is the duty ratio calculated at rated dc link voltage, 130 V ($V_{dc, max}$) and peak value of supply voltage, 170v. Hence, to achieve a DCM, the value of magnetizing inductance of HFT (L_m) is selected lower than L_{mc} [9]. Therefore, the value of *Lm* is selected around 1/10th of L_{mc}, i.e., 250 ¼H to achieve a discontinuous current conduction.

The value of output inductor is given by [10]

$$L_o = \frac{V_{dc}(1 - D_b)}{f_s(kI_o)} = 4.188mH \tag{9}$$

This output inductor is designed for rated dc link voltage of 130 V ($V_{dc, max}$,) for a minimum value of duty ratio (D_b) corresponding to a peak of maximum supply voltage of 270V [10].

Where k represents the percentage ripple of the output inductor current which is taken as 40% of output inductor current (k).Therefore, an output inductor of 4.2 mH is selected.

An expression for intermediate capacitor ($C1$) for maximum value of V_{dc} is [10]

$$C_1 = \frac{V_{dc}(D_b)}{\eta(V_{dcmax} + \sqrt{2}V_{smax})f_s}\left(\frac{P_i}{V_{dc}^2}\right)$$

$$= 456\ \mu F \tag{10}$$

Where η is the permitted ripple voltage across the intermediate capacitor and is taken as 10% of V_{c1}.

The value of dc link capacitor (Cd) for minimum dc link voltage, i.e., 50 V and is calculated as [10]

$$C_d = \left(\frac{P_i}{V_{dc}}\right)\frac{1}{2\omega\,\eta\,(V_{dc,\ min})}$$

$$= 2200\mu F \tag{11}$$

Where η represents the percentage of permitted dc link voltage ripple which is selected as 3% of $V_{dc,\ min}$.

Therefore, the dc link capacitor with the nearest value of 2200 µF is selected for this application.

A low-pass LC filter is used to avoid higher order harmonics in the supply system. The maximum value of filter capacitance (C_{max}) is given as [11]

$$C_{max} = \left(\frac{P_{max}\sqrt{2}/V_s}{\sqrt{2}V_s\omega_L}\right)\tan(\theta)$$

$$= 330\ nF \tag{12}$$

Where θ is the displacement angle between the fundamental component of supply voltage and supply current which is taken as 1°. Thus, a filter capacitor C_f of 330 nF is selected.

The value of filter inductor is designed by considering the source impedance (Ls) of 3% of the base impedance. Hence, the additional value of inductance required (Lf) is given as

$$L_f = \left(\frac{1}{4\pi^2 \times f_c^2 \times C_f}\right) - 0.03\left(\frac{1}{\omega L}\right)\left(\frac{V_s^2}{P_o}\right)$$

$$= 2.34mH \tag{13}$$

Where f_c is the cut off frequency which is selected such that $f_L < f_c < f_S$. Therefore, f_c is taken as $f_s/10$. The LC filter with inductance L_f and capacitance C_f is selected as 3.77 mH and 330 nF, respectively.

V. SIMULATION OF ISOLATED ZETA CONVERTER FED BLDC DRIVE

An isolated zeta converter fed BLDC drive is simulated using MATLAB Simulink and the results were studied. The simulink model is shown below.

The figure shows the DC link output voltage of isolated zeta converter fed brushless DC motor drive. The DC link ouput is found to be 103.5 V.

The Stator current, emf and speed waveforms are shown below. The obtained value of Stator current (I_α) is 2A, emf is 40V, Speed is 1246 Rpm.

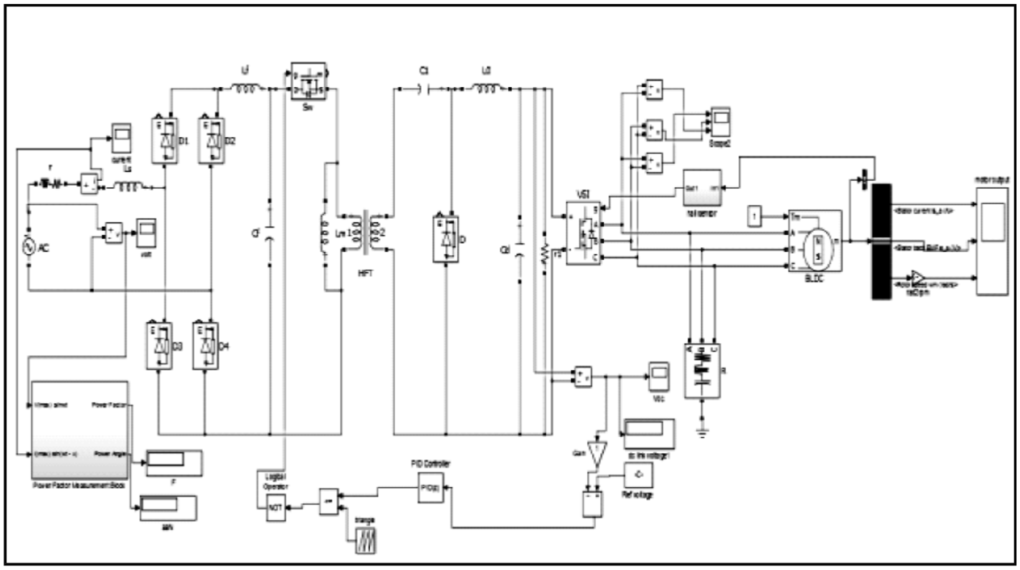

Figure 3: Simulation of Isolated Zeta fed BLDC Motor

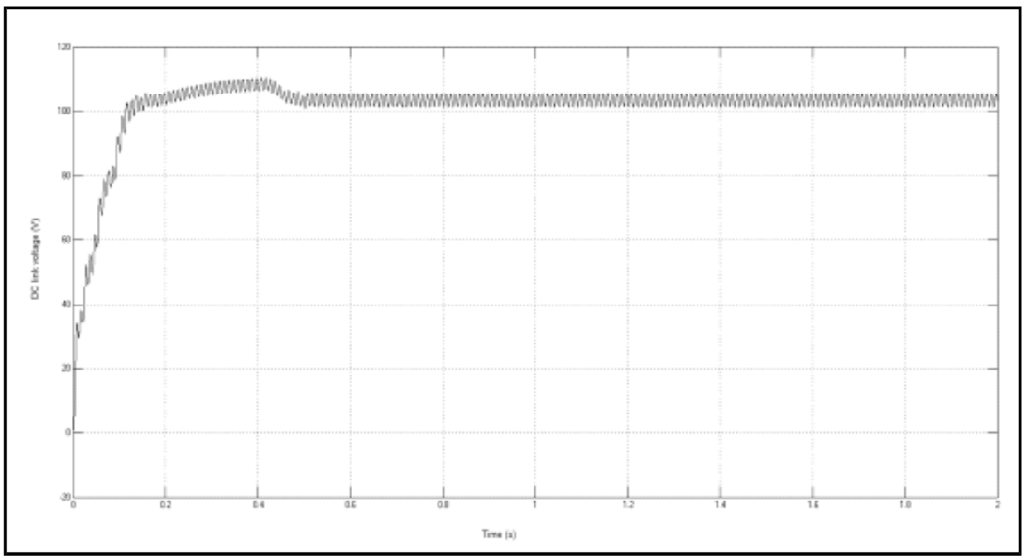

Figure 4: DC link output voltage

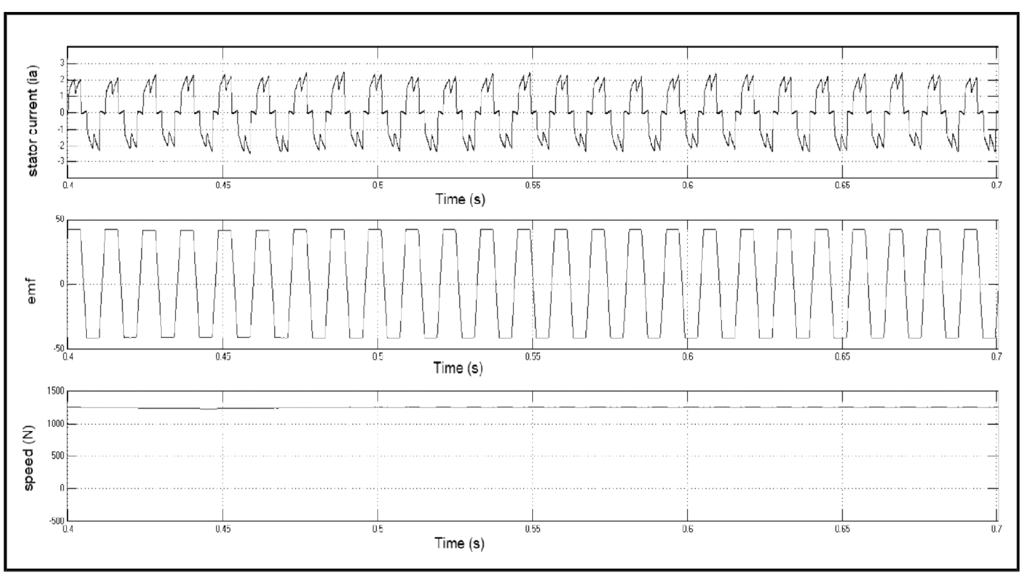

Figure 5: Stator current, emf and speed of BLDC motor drive.

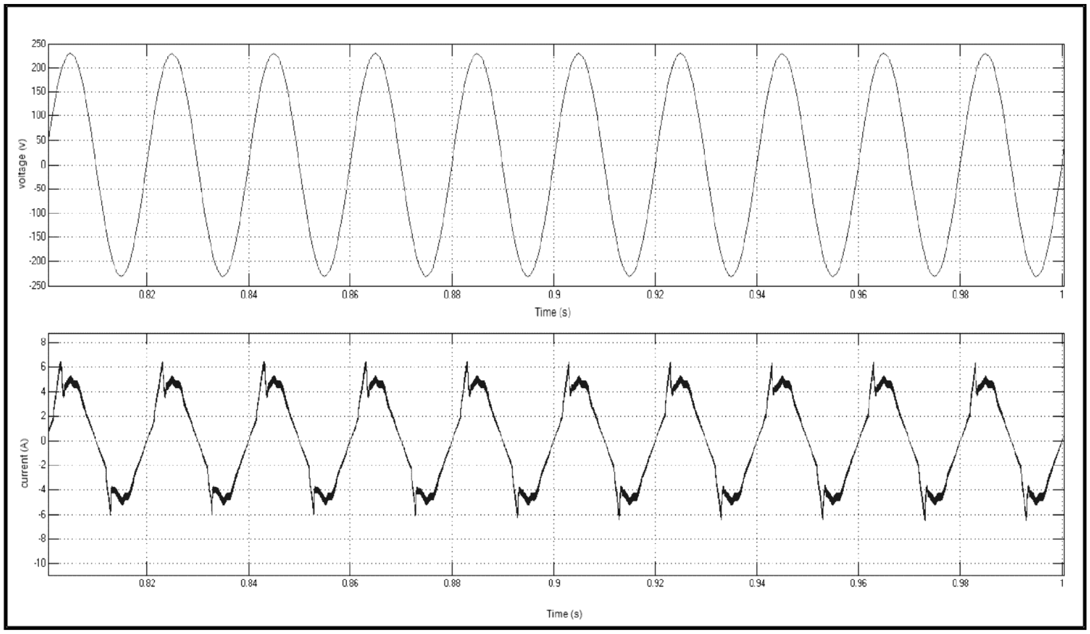

Figure 6: Voltage and current at input AC mains.

The above figure shows the input current and voltage waveforms. Current is found to be 6A and voltage 230V.

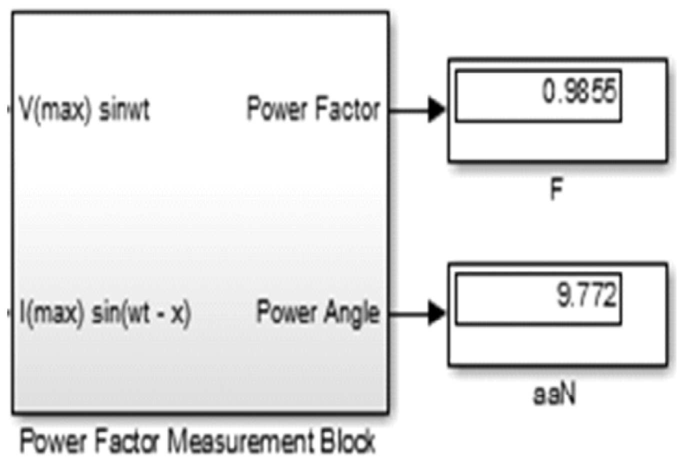

Figure 7: Measured power factor

From the above figure the measured power factor is 0.9855. Thus power factor value obtained at the input a.c mains is found to be efficient. Figure 8 shows the total harmonic distortion of the input supply current feeding isolated zeta converter fed BLDC drive. The total harmonic distortion is found to be 16.05%.

Table I
The variation of speed, power factor and input current for different DC link voltages

DC LINK VOLTAGE	*SPEED*	*POWER FACTOR*	*INPUT CURRENT THD*
49.95	550	0.9698	19.58
90.1	1071	0.9862	18.40
99	1189	0.9843	16.71
103.5	1246	0.9855	16.05
121.1	1479	0.9931	13.87

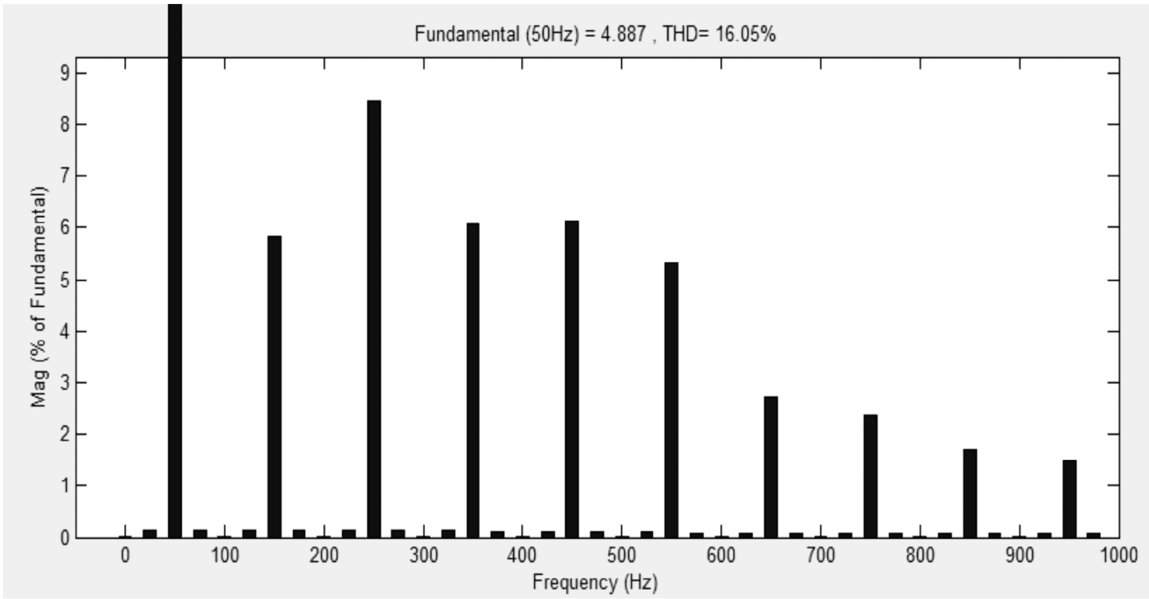

Figure 8: THD of the input supply current

A comparison between the variation of speed, power factor and input current for different DC link voltages is tabulated in table 1. It is observed that the power factor has effectively improved over wide range of speed control.

VI. CONCLUSION

An isolated zeta converter fed BLDC motor drive has been presented targeting low-power household appliances. A front-end isolated zeta converter operating in DCM has been used for DC link voltage control. The speed of BLDC motor is varied by varying the DC link voltage. The three phase VSI has been switched at low-frequency there by reducing switching losses. The drive has been simulated and results were obtained. The zeta converter is found to be effective in improving the power factor of the BLDC motor drive.

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APPENDIX

BLDC MOTOR SPECIFICATIONS: No. of poles: 4, rated dc bus voltage (V_{dc}): 130 V, rated speed ($\acute{E}_{r}$): 1500 rpm, rated torque (T_{rated}): 1.2 Nm, rated power (P_{rated}): 188.49 W, voltage constant (k_{v}): 57.59 V (peak–peak)/krpm, torque constant (k_t): 0.55 Nm/A (peak–peak), stator winding per phase resistance (R_{ph}): 4.32 Ω, stator winding per phase inductance (L_{ph}): 8 mH, moment of inertia (J): 1.8 kg ,Controller gains: $\kappa_p = 0.3$, $\kappa_i = 0.001$.