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Powerfactor Correction Based Zeta Converter Fed BLDC Motor Drive

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Abstract: This work deals with the design and simulation of a power factor correction based zeta converter fed Brushless DC (BLDC) motor drive as a cost effective solution for low power applications. Zeta converter operating in discontinuous inductor current mode (DICM) is used to feed a voltage source inverter (VSI) driving a BLDC motor. A Power Factor Corrected Zeta converter is designed to operate in discontinuous inductor current mode to provide an inherent Power Factor Correction at ac mains. The performance of the proposed drive is evaluated over a wide range of speed control and varying supply voltages with improved power quality at ac mains. An approach of speed control of the BLDC motor by controlling the dc link voltage of the voltage source inverter is used with a single voltage sensor. This facilitates the operation of voltage source inverter at fundamental frequency switching by using the electronic commutation of the BLDC motor which offers reduced switching losses. The proposed BLDC motor drive is designed and its performance is simulated in MATLAB/ Simulink environment for achieving an improved power quality at AC mains for a wide range of speed control. The proposed converter can be useful in various applications such as heating, household equipment, industrial tools, ventilation, air conditioning, medical equipment, precise motion control systems.

Key words: Brushless dc (BLDC) motor · Voltage Source Inverter (VSI) · Diode Bridge Rectifier (DBR) · continuous conduction mode (CCM) · Discontinuous conduction mode (DCM) · Power factor correction (PFC) · Power quality (PQ)

INTRODUCTION

Brush Less DC (BLDC) motors are suggested for many low and medium-power drives applications because of their high efficiency, high flux density per unit volume, low maintenance requirement, low electromagnetic interference (EMI) problems, high ruggedness and a wide range of speed control [1], [2]. Due to these advantages, they find applications in numerous areas such as household application, transportation (hybrid vehicle), aerospace, heating, ventilation and air conditioning, motion control and robotics, renewable energy applications [3-9], etc. The BLDC motor is a three-phase synchronous motor consisting of a stator having a three-phase concentrated windings and a rotor having permanent magnets [10], [11]. It does not have mechanical brushes and commutator assembly; therefore, wear and tear of the brushes and sparking issues as in case of conventional dc machines are removed in BLDC motor and so it has low EMI problems. This motor is also referred as an electronically commutated motor since an electronic commutation based on the Hall-effect rotor position signals is used rather than a mechanical commutation.

There is a necessity of an improved power quality (PQ) as per the international PQ standard IEC 61000-3-2 which recommends a high power factor (PF) and low total harmonic distortion (THD) of ac mains current for Class-A applications (<600 W, <16 A) which contains many household equipment's [12]. The conventional scheme of a BLDC motor fed by a diode bridge rectifier (DBR) and a high value of dc-link capacitor draws a non-sinusoidal current, from ac mains which is rich in harmonics such that the THD of supply current is as high as 65%, which results in PF as low as 0.8 [13]. These types of PQ indices cannot comply with the international PQ standards such as IEC 61000-3-2 [12]. Hence, single-phase power factor correction (PFC) converters are used to attain a unity PF

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at ac mains [14], [15]. These converters have increased attention due to single-stage requirement for dc-link voltage control with unity PF at ac mains. It also has low component count as compared to a multistage converter and therefore offers reduced losses [15].

Conventional schemes of PFC converter-fed BLDC motor drive use an approach of constant dc-link voltage of the VSI and controlling the speed by controlling the duty ratio of high frequency pulse width modulation (PWM) signals [16]. The losses of VSI in such type of configuration are extensive since switching losses depend on the square of switching frequency. Bridgeless configurations of PFC buck–boost, Cuk, SEPIC converters have been proposed in [13-16], respectively. These configurations offer reduced losses in the front-end converter but at the cost of high number of passive and active components. Choice of operating mode of the front-end converter is a tradeoff between the allowed stresses on PFC switch and cost of the overall system. Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are the two different modes of operation in which a front-end converter is designed to operate [14], [15].A voltage follower approach is one of the control techniques which is used for a PFC converter functioning in the DCM. This voltage follower technique requires a single voltage sensor for controlling the dc-link voltage with a unity PF. Hence, voltage follower control has an advantage over a current multiplier control of requiring a single voltage sensor. This makes the control of voltage follower a simple way to achieve PFC and dc-link voltage control, but at the cost of high stress on PFC converter switch [14], [15]. On the other hand, the current multiplier approach offers low stresses on the PFC switch, but needs three sensors for PFC and dc-link voltage control [14], [15]. Depending on design parameters, either approach may force the converter to operate in the DCM or CCM. In this work, a BLDC motor drive fed by a PFC Zeta converter operating in DICM (Lo) is examined for variable supply and different loading conditions with unity PF at ac mains which include a DICM technique with voltage follower control. The performance of proposed converter is simulated by using MATLAB/Simulink and results are tabulated for harmonic analysis.

Proposed PFC-Based BLDCMotor Drive: Fig. 1 shows the proposed PFC Zeta converter-fed BLDC motor drive. A single-phase supply is used to feed a DBR followed by a ?lter and an Zeta converter. The ?lter is designed to avoid any switching ripple in the DBR and the supply system. An 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 BLDC motor is commutated electronically to operate the IGBTs of VSI in fundamental frequency switching mode to reduce its switching losses. The current flowing in either of the input or output inductor (Li and Lo) or the voltage across the intermediate capacitor (*C*1) becomes discontinuous in a switching period for a PFC Zeta converter operating in the DCM. A Zeta converter is designed to operate in all three DCMs of operation and its performance is evaluated for a wide voltage control with unity PF at ac mains.

Operation of PFC Zeta Converter: The operation of the Zeta converter is studied in discontinuous inductor current mode (DICM). In the DICM, the current flowing in inductor *Lo* becomes discontinuous in their respective modes of operation. The operation of an 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. 2(d). These modes are described as follows

Interval I: When switch (S_w) is turned "ON, " a current in magnetizing inductance (L_m) of high frequency transformer (HFT) increases as shown in Fig. 2(a). The intermediate capacitor (C_1) supplies energy to an output inductor (L_o) and the dc link capacitor (C_d). Hence, voltage across intermediate capacitor (V_{C1}) reduces and the current in output inductor (i_{Lo}) and dc link voltage (V_{dc}) are increased as shown in Fig. 2(d).

Interval II: When switch (S_w) is turned "OFF, " the current in magnetizing inductance (L_m) of HFT and output inductor (L_o) starts reducing. This energy of HFT is transferred to the intermediate capacitor (C_1) and therefore voltage across it increases. Diode (D) conducts in this mode of operation and the dc link voltage (V_{dc}) increases as shown in Fig. 2(b).

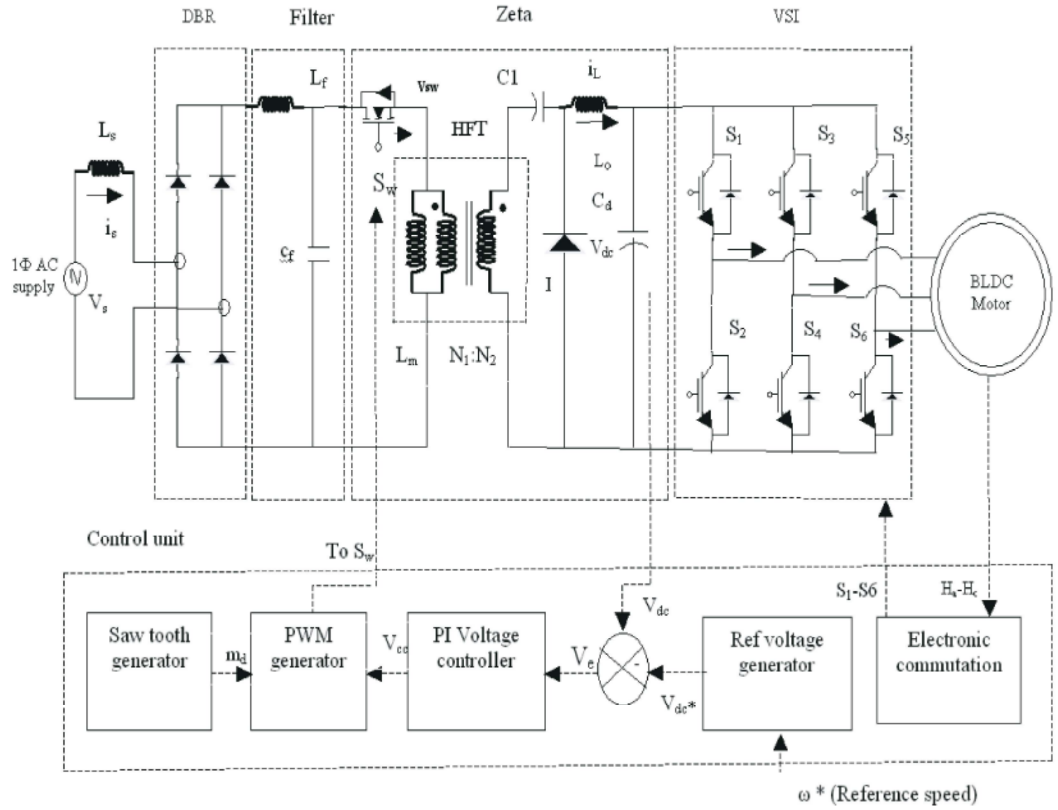

Fig. 1: BLDC motor drive fed by a PFC Zeta converter using a voltage follower approach

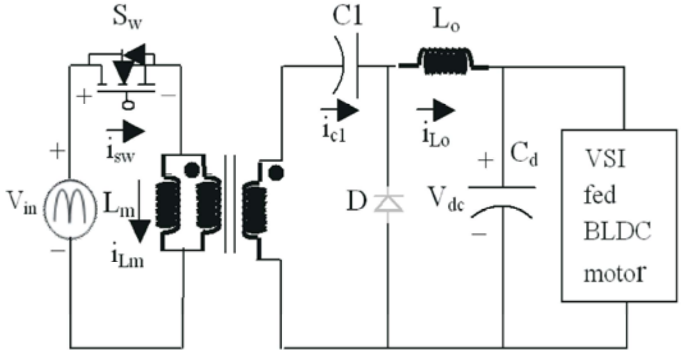

Fig. 2(a): Operation of the Zeta converter Interval- I

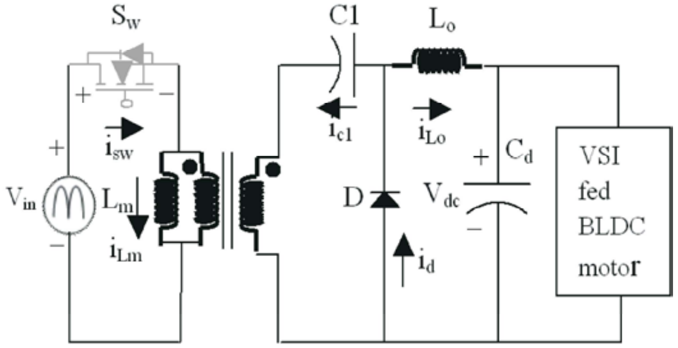

Fig. 2(b): Operation of the Zeta converter Interval- II

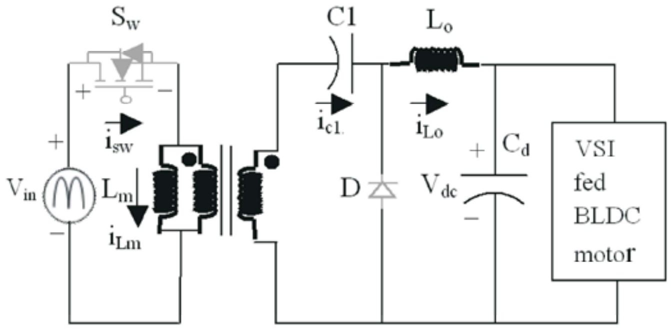

Fig. 2(c): Operation of the Zeta converter Interval- III

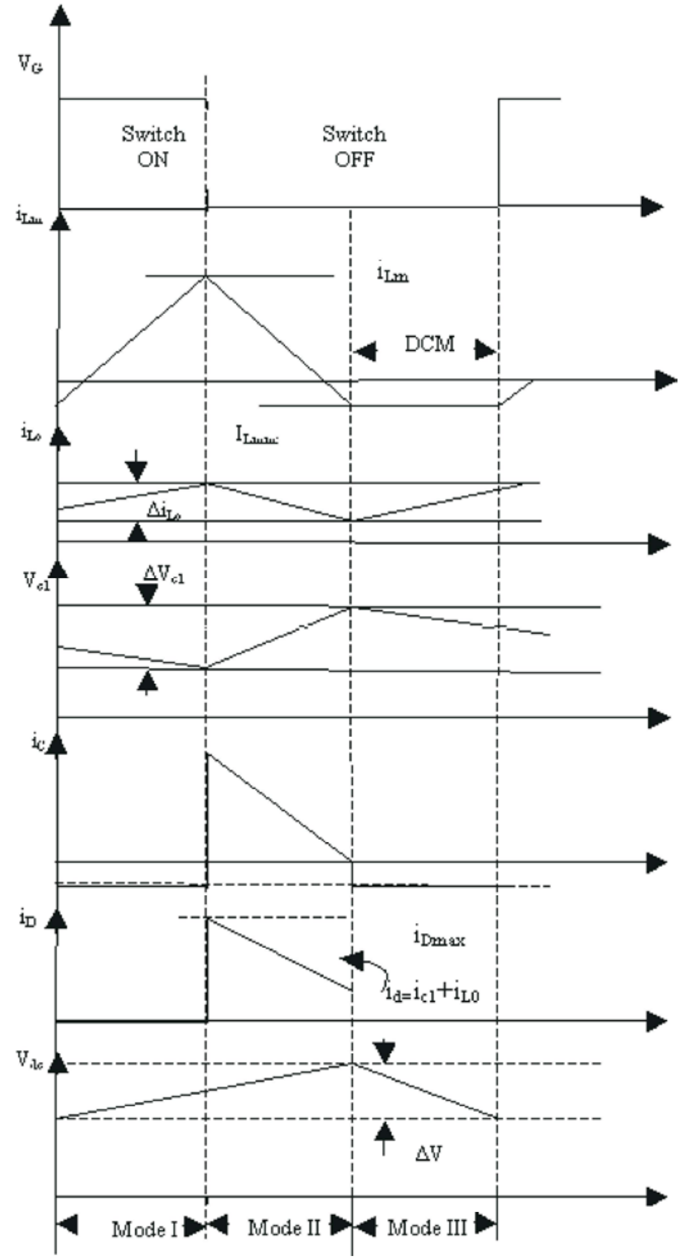

Fig. 2(d): Operating waveforms of an Zeta converter

Interval III: This mode is DCM such that the energy of HFT is completely discharged as shown in Fig. 2(c). 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's voltage (V_{C1}) are reduced and the output inductor current increases in this mode of operation as shown in Fig. 2(d).

Design of Converter Parameters: A PFC-based Zeta converter-fed BLDC motor drive is designed for dc-link voltage control of VSI with PFC at the ac mains. 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. The Zeta converter is designed for DICM. The design and selection criterion of this parameter is discussed in the following section.

The input voltage *Vs* applied to the DBR is given as:

$$V_s(t) = V_m \sin(2\pi f_L t) = 220\sqrt{2}\ Sin\ (314t)\ V \qquad (1)$$

where *Vm* is the peak input voltage (i.e., *v*2*Vs, Vs* is the rms value of supply voltage) and f_L is the line frequency, i.e., 50Hz.

The instantaneous voltage appearing after the DBR is as follows:

$$V_{in}(t) = |V_m Sin(\omega t)| = |\ 220\sqrt{2}\ Sin(314t)|V \qquad (2)$$

where ||represents the modulus function.

The output voltage *V*dc of the Zeta converter is given as [15];

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

where *D* represents the duty ratio and 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 appearing after DBR *V*in (*t*) and the required dc link voltage *V*dc. Hence, the instantaneous duty ratio *D*(*t*) is obtained by substituting (2) into (3) and rearranging it as:

$$D(t) = \frac{V_{dc}}{\frac{N_2}{N_1}V_{in}(t) + V_{dc}}$$

$$= \frac{V_{dc}}{(\frac{N_2}{N_1})|V_m \sin(\omega t)| + V_{dc}} \qquad (4)$$

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

$$Pi = \left(\frac{P_{\max}}{V_{dc\max}}\right)V_{dc} \qquad (5)$$

where ☻ represents maximum dc link voltage and ☻ is the rated power of the PFC converter. Using (5), the minimum power (☻) corresponding to the minimum dc link voltage (☻). The critical value of magnetizing inductance of the HFT(☻) is expressed as;

$$L_{mc} = \frac{R_L\{1-D(t)\}^2}{2D(t)f_s(N_2/N_1)^2}$$

$$= \left(\frac{V_{dc}^2}{P_i}\right)\frac{(1-D(t)\}^2}{2D(t)f_s(N_2/N_1)^2}$$

$$= \left(\frac{V_{dc}^2}{P_i}\right)\frac{\{1-D(t)\}^2}{2D(t)f_s(N_2/N_1)^2} \qquad (6)$$

where ☻ represents the emulated load resistance, ☻ is theswitching frequency and ☻ is theinstantaneous power. The expression for calculation of output inductor is as;

$$L_o = \frac{V_{dc}(1-D(t)}{f_s \Delta i_{Lo}}$$

$$L_o = \frac{V_{dc}\{1-D(t)\}}{f_s(kI_o)} \qquad (7)$$

An expression for intermediate capacitance ☻ is as;

$$C_1 = \frac{V_{dc}D(t)}{\Delta V_c(t) f_s R_L}$$

$$= \frac{V_{dc}D(t)}{\eta\{\sqrt{2V_s} + V_{dc}\}f_s}(\frac{P_i}{V_{dc}{}^2}) \qquad (8)$$

where η is the permitted ripple voltage across intermediate capacitor.

The value of the dc-link capacitor ☻ is calculated by;

$$C_d = \frac{I_{dc}}{2\omega \Delta V_{dc}}$$

$$= (\frac{P_i}{V_{dc}})\frac{1}{2\omega\eta V_{dc}} = \frac{P_i}{2\omega\eta V_{dc}^2} \qquad (9)$$

where Δ ☻ represents the permitted ripple in dc link voltage, η represents the percentage of permitted dc link voltage.

Simulation Results: The performance of the Zeta converter-fed BLDC motor drive is simulated and analyzed for three different loading conditions in MATLAB/Simulink environment. The performance of DICM operation is evaluated on the basis of various performance parameters.

The proposed converter was simulated by using MATLAB/Simulink under various loading conditions. The Fig. 3-Fig. 8 shows the dynamic response of BLDC drive with proposed converter. The simulation results are tabulated for easy analysis. The results are indicate that the PF is maintained almost constant and nearer to unity.

Dynamic Response at No Load Condition:

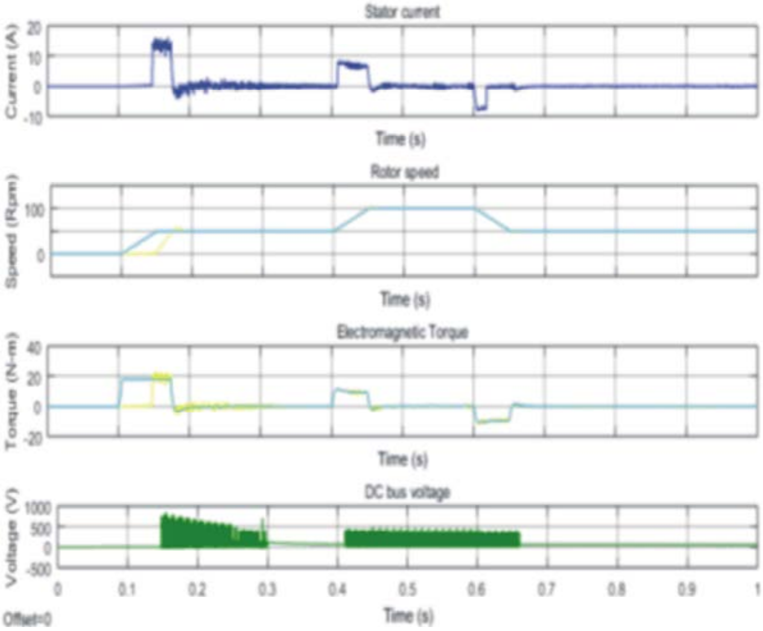

Fig. 3: Dynamic response of BLDC drive at no load

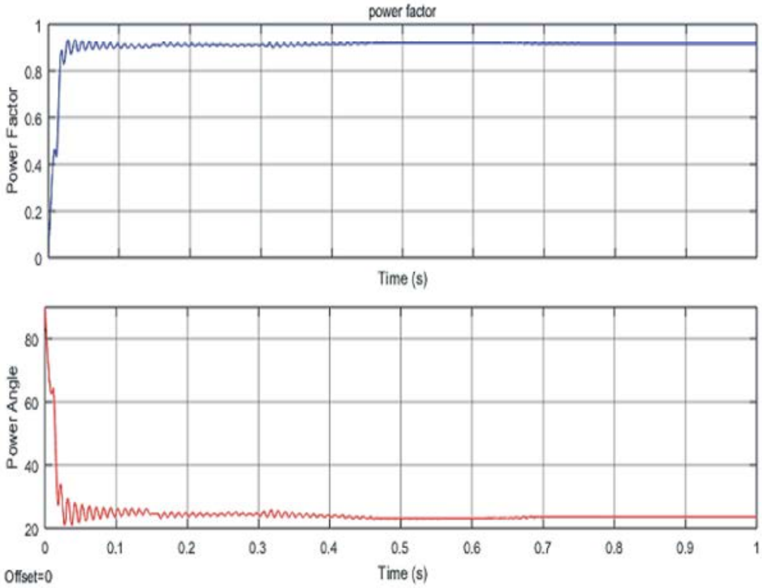

Fig. 4: Power factor & Power angle for no-load

Table 1: Motor & Drive parameters under supply voltage variations at No Load

Sl. No.	I/P Vol (V)	I/P Current (A)	O/P Vol (V)	O/P Current (A)	Rotor Speed (RPM)	Power Angle	Power Factor
1	100	0.0079	29.75	0.267	50	21.38	0.9312
2	120	0.0095	-2.99	0.5608	50	23.24	0.9188
3	140	0.0112	51.89	0.0071	50	23.24	0.9189
4	160	0.0772	289.7	-0.287	50	23.26	0.9187
5	180	0.0144	-5.19	-0.287	50	23.21	0.9191
6	200	0.0158	64.22	-0.1907	50	23.61	0.9163

Dynamic Response at Half Load Condition:

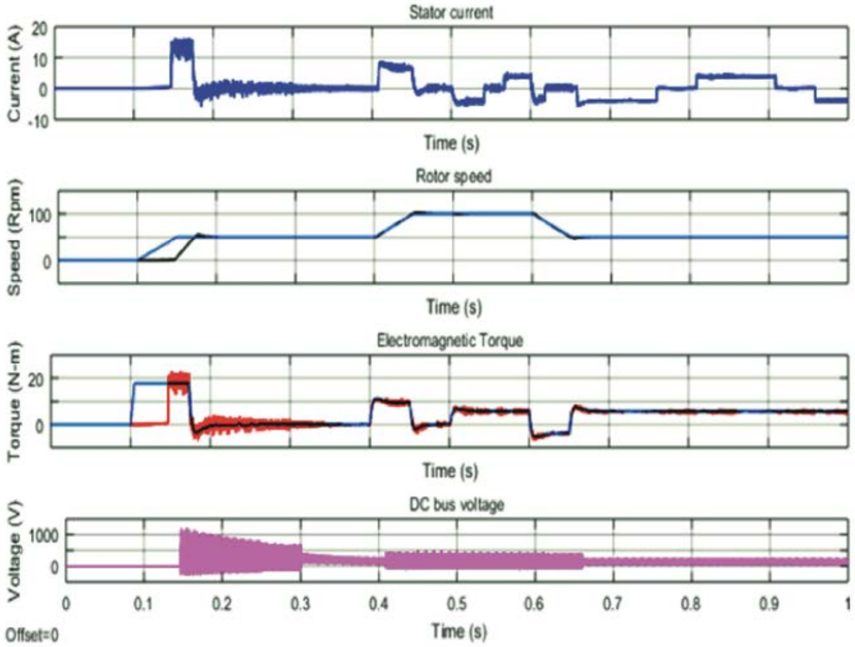

Fig. 5: Dynamic response of BLDC drive at half load

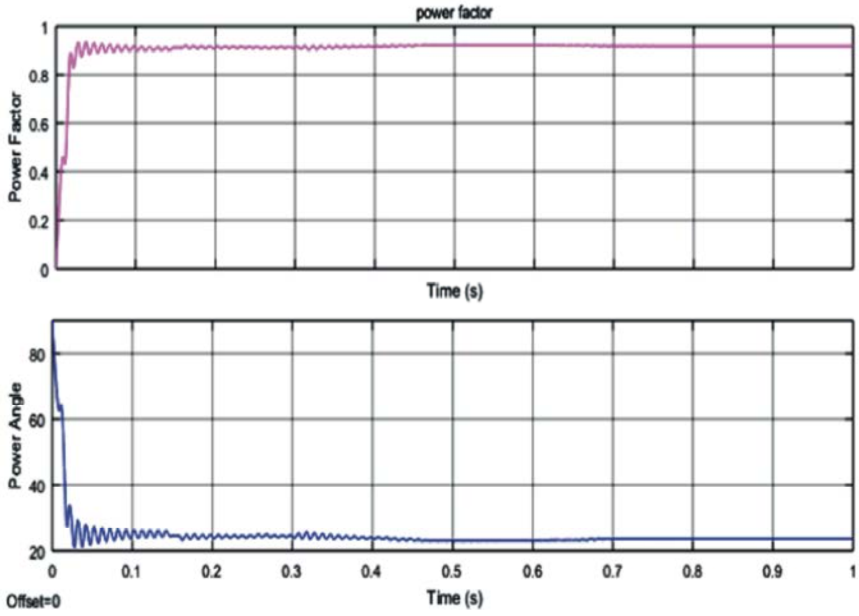

Fig. 6: Power factor & Power angle for half-load

Table 2: Motor & Drive parameters under supply voltage variations at Half Load

Sl. No.	I/P Vol (V)	I/P Current (A)	O/P Vol (V)	O/P Current (A)	Rotor Speed (RPM)	Power Angle	Power Factor
1	100	0.007	70.4	3.68	50	21.4	0.931
2	120	0.0095	211.9	-0.1524	50	23.26	0.9187
3	140	0.1121	52.4	-0.1524	50	23.24	0.9189
4	160	0.01273	281	-3.936	50	23.26	0.9187
5	180	0.0144	-5.95	-4.584	50	23.21	0.9191
6	200	0.0158	64.21	-4.26	50	23.61	0.9163

Dynamic Response at Full Load Condition:

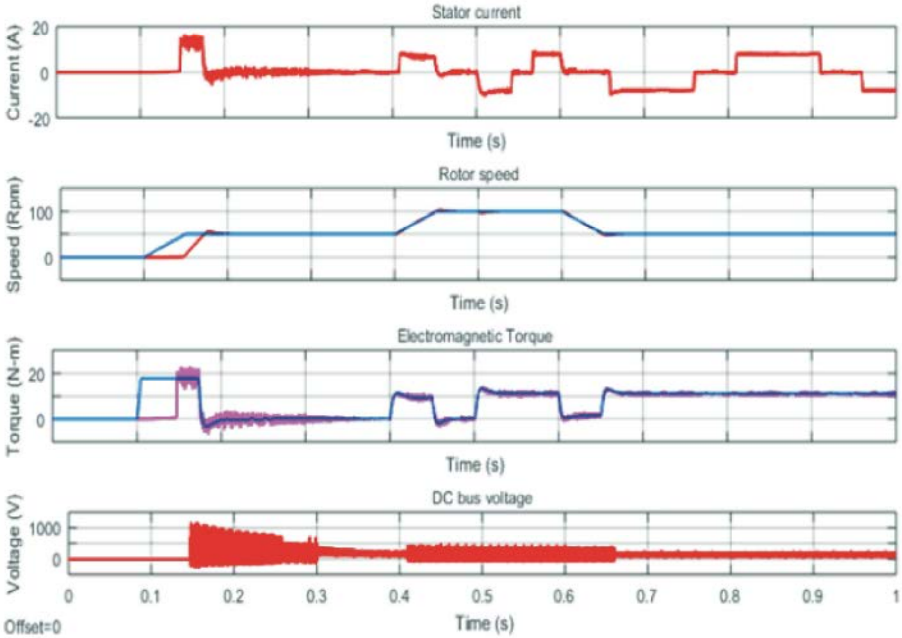

Fig. 7: Dynamic response of BLDC drive at full load

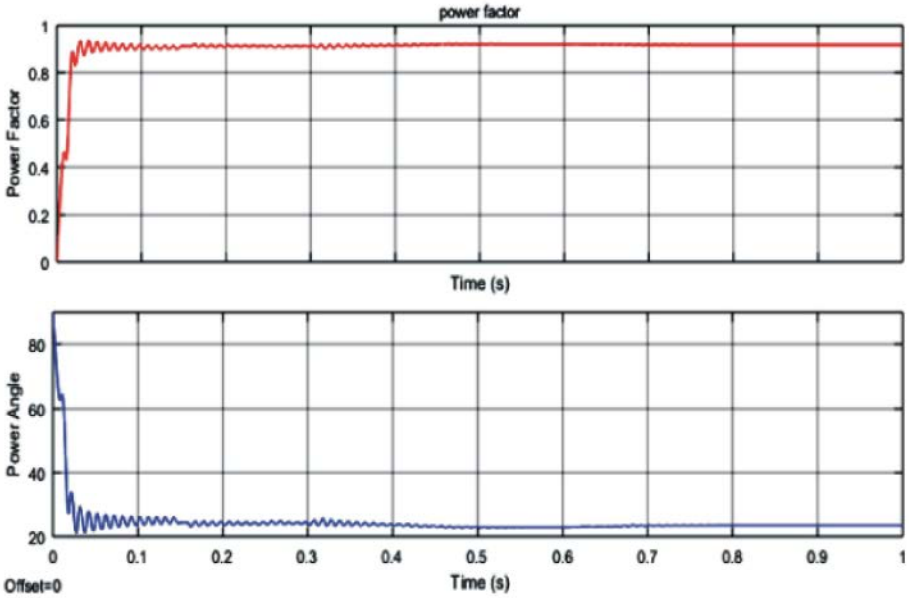

Fig. 8: Power factor & Power angle for full-load

Table 3: Motor & Drive parameters undersupply voltage variations at Full Load

Sl. No.	I/P Vol (V)	I/P Current (A)	O/P Vol (V)	O/P Current (A)	Rotor Speed (RPM)	Power Angle	Power Factor
1	100	0.0079	25.14	.8138	50	21.38	0.9321
2	120	0.00954	212.8	0.0586	50	23.26	0.9187
3	140	0.01121	52.45	-0.0265	50	23.24	0.9189
4	160	0.01273	284.3	-7.725	50	23.26	0.9187
5	180	0.0114	-5.19	-8.078	50	23.21	0.9191
6	200	0.01589	62.35	-7.442	50	23.61	0.9163

CONCLUSION

A Zeta converter for VSI-fed BLDC motor drive has been designed for achieving a unity PF at ac mains for the development of the low-cost PFC motor for numerous low-power equipment's such fans, blowers, water pumps, etc. The speed of the BLDC motor drive has been controlled by varying the dc-link voltage of VSI, which allows the VSI to operate in the fundamental frequency switching mode for reduced switching losses. Three different intervals of operation for the Zeta converter operating in the DICM have been explored for the development of the BLDC motor drive with PF near to unity at ac mains. The proposed drive system has shown satisfactory results in all aspects and is a recommended solution for low-power BLDC motor drives.

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