

Improved Source-End Current power Quality Performance of a BLDC Motor Drive Using a Novel DC-DC Converter

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Abstract — This paper presents a brushless DC (BLDC) motor drive with power factor correction (PFC) for low power and high speed applications. In this study, the speed of the BLDC motor is controlled by adjusting the DC link voltage of the voltage source inverter (VSI). A novel PFC based Non-isolated Zeta Fly-back converter operating in discontinuous conduction mode (DCM) is used for controlling the DC link voltage of the VSI by exploiting single voltage sensor. Utilizing the zeta converter and its valuable property in reducing output current ripple and its inherently power factor correction capability and interleaving fly-back converter to zeta and using its high gain property, this converter can be a good choice for interfacing BLDC motors drive. The MATLAB/ SIMULINK environment is used to simulate the proposed model to achieve a wide range of speed control with near unity power factor at AC mains and improved PQ (Power Quality) based on IEC 61000-3-2 standard.

Keywords— Non-isolated zeta-flyback converter; power factor correction; brush-less DC motor drive.

I. INTRODUCTION

Recently, the brushless DC (BLDC) motors have become more important because of their high efficiency, high torque per inertia ratio, minimum maintenance requirements, high reliability, and less electro-magnetic interference (EMI) problems [1]. The BLDC motor is a three phase synchronous motor having torque–speed characteristics similar to a conventional DC motor [2]. It is also known as electronically commutated motor since an electronic commutation based on rotor position is used [2]. This eliminates the noise, sparking and maintenance problems in the DC motors [3]-[5].

The requirement of international power quality standards has recommended the use of power factor correction converters with a brushless DC motors for low power applications [6]. In the traditional topologies, the BLDC motors are fed from a single-phase AC supply through a diode bridge rectifier (DBR) followed by a DC capacitor and a VSI, which is commutated based on rotor position. However, this configuration results in a pulsed current from AC supply having various power quality (PQ) problems such as poor power factor (PF), increased total harmonic distortion (THD) and high crest factor (CF) of current [6]. This is due to uncontrolled charging of the DC capacitor that degrades the harmonic performance of the motor [7]. Therefore, the use of a suitable power factor correction converter topology

is an essential requirement for a BLDC motor drive. Many configurations of PFC converter feeding a BLDC motor are available in the literature [8],[9]. The boost PFC converter has been the traditional configuration for improving the power quality [10],[11]. Zeta based converters has been widely used as a PFC, because of its fast dynamic performance, and inherently Power factor correction property [1]. Some isolated Zeta converters have been studied in [12]-[16] for power factor correction applications. Fly-back converter has the advantage of circuit simplicity and less component counts and its transformer has the ability to store energy [17]. Lin & Hsieh [18] proposed an isolated zeta fly-back converter, which utilizes a buck-boost active clamp. In this converter only transformer is used to provide power from input to output side and current stress on primary windings are much higher and size of magnetic core is large. The choice of operation of PFC converters in CCM or DCM is determined based on power rating [10]. CCM offers lower switch stresses, but utilizes a complex control system and requires more sensors, which is not a cost effective solution and preferred for high power rating [10]. Whereas, DCM uses a simple approach of output voltage control, which requires a single voltage sensor but with the higher stresses on the switches [19, 22].

In this paper a novel non-isolated zeta fly-back converter is proposed for power factor correcting of BLDC motors. The proposed PFC drive is designed and its performance is simulated for a 12000 rpm and 500 watt BLDC motor that can improve power quality at AC mains. Steady state analysis of the converter has been provided too. The operation of the converter is in discontinuous conduction mode and hence voltage follower approach is used. The MATLAB/ Simulink environment is used to validate the results.

II. PROPOSED PFC BASED BLDC MOTOR DRIVE

In this section, the proposed PFC based DC-DC converter and its operation mode are introduced.

A. Configuration of the Proposed PFC Topology

Fig. 1 shows the proposed PFC non-isolated zeta fly-back converter fed BLDC motor drive. A single-phase supply is used to feed a diode bridge rectifier (DBR) followed by a filter and a

non-isolated zeta fly-back converter. A non-isolated zeta fly-back converter is designed to operate in DCM to act as an inherent power factor corrector [1]. 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. Specifications of the simulated BLDC motor are given in Table I.

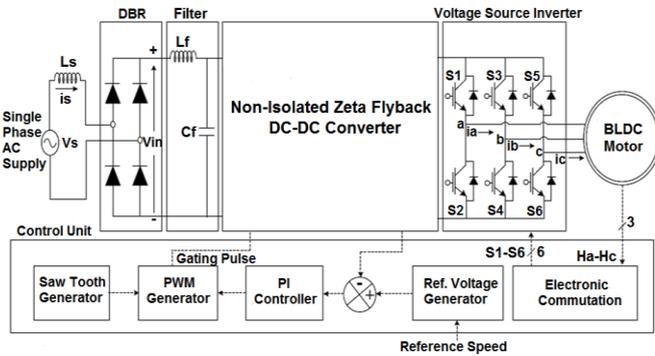


Fig. 1. Proposed PFC converter fed BLDC motor drive.

The DC link voltage of the VSI is controlled by varying the duty ratio of the PWM pulses of PFC converter switch. A single voltage sensor is used at the PFC converter for the control of DC link voltage and speed of BLDC motor.

B. Operation of Non-isolated Zeta Fly-back Converter

The proposed converter is a non-isolated zeta fly-back converter, which is depicted in Fig. 2. This converter consists of two parts: A zeta converter part and a fly-back part which has been coupled together through a coupling inductor.

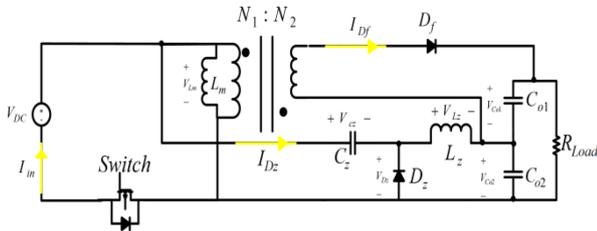


Fig. 2. Proposed non-isolated zeta fly-back converter.

Prior to starting the analysis of the proposed converter, there are some assumptions:

- Capacitors C_1 , C_2 and C_z are large enough that voltage across them remains constant.
- Inductor L_m is large enough that its current is constant.
- All of the circuit elements are ideal.

Steady state analysis of this part contains two modes. The first mode is when switch of the circuit is on and second mode is the time switch is off.

Mode 1 [t_0, t_1]: This mode starts at $t = t_0$ when the gate voltage is applied to the gate of the switch. Equivalent circuit of this mode is depicted in Fig. 3. Currents I_{Df} and I_{Dz} are zero during this mode, which means diodes D_f and D_z are off.

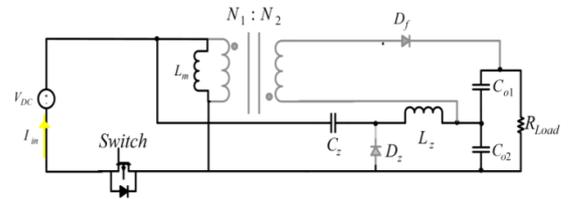


Fig. 3. Equivalent circuit during mode 1 of steady state.

Mathematical analysis of this mode could be followed as the following equations indicate,

$$V_{L_m} = V_{in} \quad (1)$$

$$V_{L_z} = V_{L_m} + V_{C_z} - V_{C_1} \quad (2)$$

where D is the duty ratio and T is the switching period.

Mode 2 [t_1, t_2]: Equivalent circuit for this mode is shown in Fig. 4. As it can be seen current I_{in} is zero but diodes D_f and D_z have non-zero currents, meaning they are conducting.

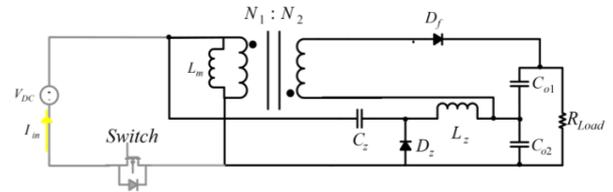


Fig. 4. Equivalent circuit during mode 2 of steady state.

$$V_{L_m} + V_{sw} = V_{in} \quad (3)$$

$$V_{C_2} = \frac{N_2}{N_1} (V_{sw} - V_{in}) \quad (4)$$

$$V_{L_m} = -V_{C_z} \quad (5)$$

To calculate the gain of the converter, volt-second balance is applied to the inductor which leads to:

$$V_{C_1} = \frac{D}{1-D} V_{in} \quad (6)$$

$$V_{C_2} = \frac{N_2}{N_1} \left(\frac{D}{1-D} \right) V_{in} \quad (7)$$

$$V_{out} = V_{C_1} + V_{C_2} = \left(1 + \frac{N_2}{N_1} \right) \left(\frac{D}{1-D} \right) V_{in} \quad (8)$$

$$V_{s_{max}} = \left(\frac{1}{1-D} \right) V_{in} \quad (9)$$

$V_{s_{max}}$ is the maximum voltage stress on the switch.

III. DESIGN OF ZETA FLY-BACK CONVERTER FED BLDC MOTOR DRIVE

A 500W PFC zeta fly-back converter is designed for VSI fed BLDC motor drive with the following specifications: P_{out} (output power) = 500W, V_s (supply voltage) = 220V, V_{dc} (DC link voltage) = 170V, f_L (line frequency) = 50 Hz, $N_2:N_1$ (transformation ratio) = 1:2, Δi_{L_m} (permitted ripple current in inductor L_m) = 10% of I_m , ΔV_{C_z} (permitted ripple voltage in intermediate capacitor C_z) = V_m (peak of input voltage), ΔV_{dc}

(permitted DC link voltage ripple) = 2% of V_{dc} , $f_s = 45\text{kHz}$ (switching frequency).

The input voltage V_s is given as,

$$V_s = V_m \sin(2\pi f_L t) = 311 \sin(314t) \quad (10)$$

The input average voltage (input voltage of the proposed DC-DC converter) is calculated as,

$$V_{in} = \frac{2V_m}{\pi} \approx 198 \text{ V} \quad (11)$$

The output voltage, V_{dc} of non-isolated zeta fly-back converter is calculated based on Eq. (8). So, duty ratio is calculated as,

$$D = \frac{V_{dc}}{V_{dc} + (1 + \frac{N_2}{N_1})V_{in}} = 0.364 \quad (12)$$

The value of equivalent load resistance (R_L) is calculated as,

$$R_L = \frac{V_{dc}^2}{P_{out}} = 57.8 \ \Omega \quad (13)$$

The critical value of magnetizing inductance L_{mc} of transformer to operate at boundary of CCM and DCM is given by,

$$L_m = \frac{V_{DC} D}{f \Delta i_{Lm}} \quad (14)$$

The value of L_m is selected as $60\mu\text{H}$ for its operation in DCM. The value of inductor L_z could be calculated through,

$$L_z = \frac{V_{DC} D}{f \Delta i_{Lz}} \quad (15)$$

The value of L_z is selected as $30\mu\text{H}$.

The value of intermediate capacitor C_z could be calculated using (16).

$$C_z = \frac{V_o D}{f R_{Load} \Delta V_{Cz}} \quad (16)$$

The value of intermediate capacitor is selected as $4.7\mu\text{F}$.

The value of DC link capacitor is given and calculated as,

$$C_1 = C_2 = \frac{I_{dc}}{2\omega_L \Delta V_{dc}} = 1377.47 \ \mu\text{F} \quad (17)$$

Hence the value of DC link capacitor is selected as $C_{dc} = C_1 + C_2 = 2200\mu\text{F}$.

An EMI filter (input LC filter) is designed to avoid the reflection of high switching frequency in the supply system [12]. The value of input filter capacitance (C_f) and inductance (L_f) is selected as 330 nF and 4 mH , respectively.

IV. CONTROL OF NON-ISOLATED PFC ZETA FLYBACK CONVERTER FED BLDC MOTOR DRIVE

The control of the proposed PFC based BLDC motor drive is divided into two section. The first section is control of PFC converter, and the second is control of three-phase VSI.

A. Control of Front-End PFC Converter

A voltage follower approach is used for the control of non-isolated zeta fly-back converter operating in DCM (as depicted in Fig. 1). A 'Reference Voltage Generator' generates a reference voltage that is proportional to the reference speed with the motor's voltage constant (k_v). The generated reference voltage is compared to the measured value and the resulted error signal is given to a PI controller. Finally the PWM signal for the main switch is generated by comparing the output of PI controller with high frequency saw-tooth signal.

B. Control of BLDC Motor

A Hall-Effect sensor is used to sense the rotor position; which is required for the electronic commutation of BLDC motor. The electronic commutation of BLDC motor includes proper switching of VSI. So, for controlling of the BLDC motor, a switching pattern selected and applied to the VSI according to the rotor position.

V. SIMULATION RESULTS

To verify the flexibility of the proposed PFC based BLDC motor, a power circuit was simulated in MATLAB /SIMULINK. The system consists of a single-phase AC supply, diode bridge rectifier, non-isolated zeta fly-back converter as a power factor corrector and BLDC motor. Parameters of the simulated system are presented in Table I and II. Fig. 5 shows that the proposed PFC converter can operate in both of DCM and CCM condition (based on value of magnetizing inductance). But, because of control algorithm simplicity, DCM is selected. Also, as depicted if Fig. 5 in DCM, voltage stresses on the switch are more than continuous mode, because in each interval, the current of L_m , should be zero. So, CCM is used for high and medium power levels and DCM for low power applications.

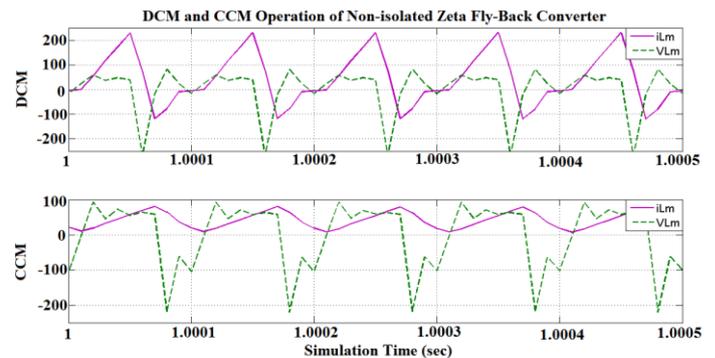


Fig. 5. Voltage and current of the magnetizing inductance in both of DCM ($L_m = 60\text{ mH}$) and CCM ($L_m = 200\text{ mH}$).

Fig. 6 indicates that for rated DC link voltage (170 volts), DCM condition has more ripples in the output voltage. In general, CCM has precise results, but more implementation costs (such as number of sensors and filter size) and complexity [3].

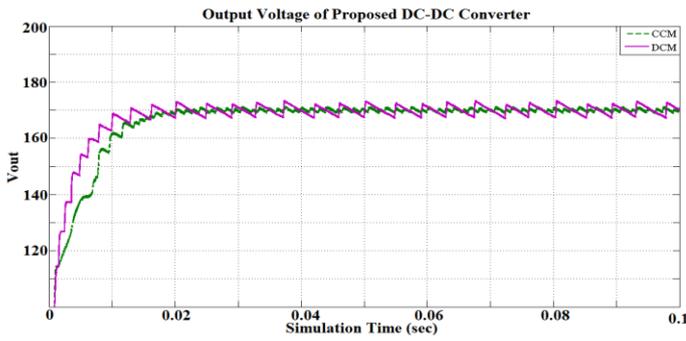


Fig. 6. Output voltage (V_{dc}) of PFC converter for DCM and CCM condition.

Fig. 7 shows the dynamic behavior of the proposed drive during step changes in reference speed at rated and no load condition. Because the rated speed of the simulated BLDC motor is 12000 rpm, for reference speed near to this value the error of control system is lower in comparison to other references. A smooth control is achieved over a wide range of speed which shows proper functionality of PFC control loop. The maximum speed that can be obtained in rated load, is 13000 rpm, and in no load condition, as depicted in Fig. 7, is less than this.

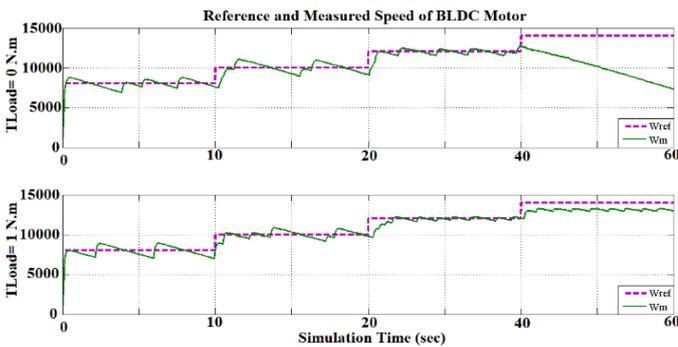


Fig. 7. Dynamic performance of the proposed drive during step change in reference speed (for rated and no load condition).

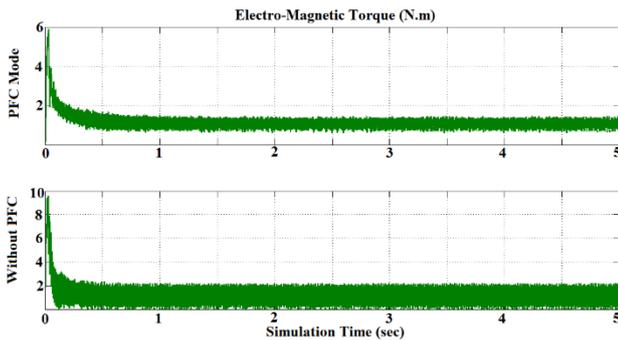


Fig. 8. Output torque of the BLDC motor, (a) case I, and (b) case II.

For comparing of PFC operation of the proposed drive system, two study case are considered. In case I, the BLDC motor is fed from single phase diode bridge rectifier without using any PFC converter. In case II, proposed PFC converter is

feeding BLDC motor. As it can be seen in Fig. 8, by using PFC converter, the ripple of output torque of the BLDC motor in rated condition is decreased.

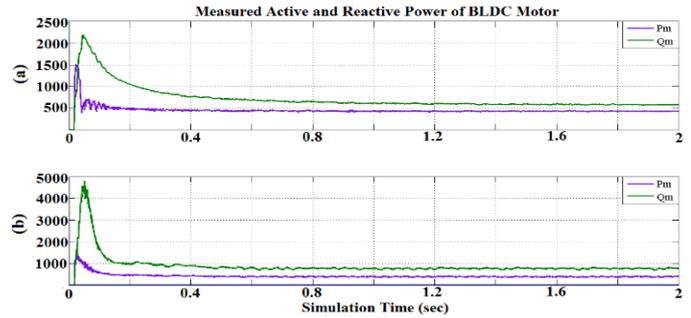


Fig. 9. Averaged active and reactive power for two case study, case I: without PFC, and case II: by using PFC based drive.

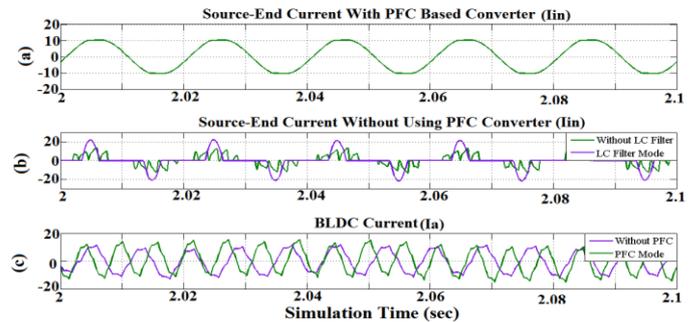


Fig. 10. (a) Source-End current by using PFC converter, (b) input current without PFC operation, and (c) BLDC motor current for each case study.

Also, as shown in Fig. 9, averaged reactive power in case II, has lower amplitude, which means by using proposed PFC converter, transferred reactive power between AC supply and BLDC motor is decreased and power quality is improved. Hence, an improved power quality is achieved for a wide range of speed control. Also, Fig. 9(a) shows, peak value of reactive power is decreased by using PFC converter.

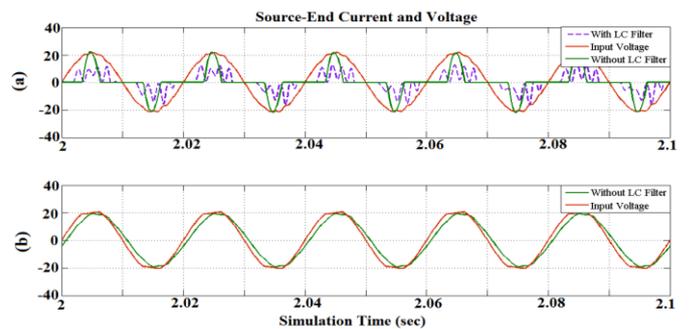


Fig. 11. Comparison of power factor correction performance, (a) case I, and (b) case II (green: source current, and red: source voltage).

Fig. 10 shows source-end current of the proposed system. As it can be seen, in case I, I_{in} produces 50% THD. But, in case II, the current of the AC source is almost a pure sinusoidal and has acceptable THD (below 5%).

Fig. 11 shows near unity power factor correcting performance of the proposed system. This demonstrates a satisfactory performance in terms of improved power quality. Harmonic spectra related to case study is depicted in Fig. 12.

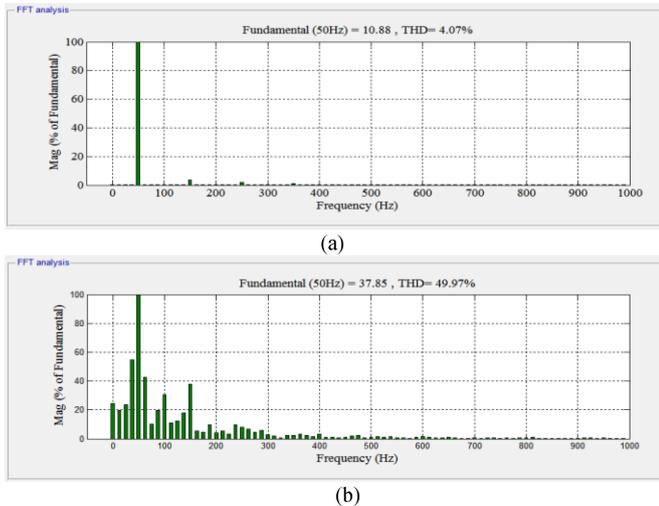


Fig. 12. Harmonic spectra of the source-end current for, (a) case II, and (b) case I.

TABLE I SPECIFICATIONS OF BLDC MOTOR

Parameters	Symbol	Value
Rated power	P_{out}	500 watt
Rated speed	ω_m	12000 rpm
Rated DC link voltage	V_{dc}	170 Volts
Stator resistance	R_s	0.28 Ω
Stator inductance	L_s	0.000835 H
Inertia	J	0.000625 kg.m ²
Amp. Of magnetic flux	λ_m	0.07145 V.s
Damping factor	B_m	0.0003035 $\frac{N.m.s}{rad}$
Frequency	f_n	50 Hz
Pole pair	P	1

TABLE II SPECIFICATIONS OF PROPOSED PFC CONVERTER

Parameters	Symbol	Value
Leakage Inductance	L_r	27 μH
Magnetizing Inductance	L_m	CCM 200 μH
		DCM 60 μH
Output Inductance	L_z	30 μH
Middle Capacitor	C_z	4.7 μF
DC Link Cap.	$C_1 + C_2$	2200 μF
Rated Power	P_n	500 watt

VI. CONCLUSION

In this paper the operation of a non-isolated zeta fly-back converter for PFC based BLDC motor drive has been developed and discussed completely. Different modes of operation and related formulas with equivalent circuit describing each mode have been prepared too. The front end non-isolated zeta fly-back converter operating in DCM has been used for DC link voltage control and PFC operation, by using a single voltage sensor. By using zeta converter and its valuable property in reducing output current ripple and inherently power factor correction capability and interleaving fly-back converter to zeta and using

its high gain property, this converter can be a good choice for interfacing BLDC motors drive. The MATLAB/ SIMULINK environment is used to simulate and validate the effectiveness of the proposed PFC converter. An improved power quality operation and lower THD of the 12000 rpm and 500 watt BLDC motor drive has been achieved with power quality requirements within the acceptable limits by IEC 61000-3-2.

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