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A New Pulse Width Modulated PFC Zeta Converter Fed Sensorless BLDC Motor Drive with Position Feedback

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Abstract: ***A New Pulse Width Modulated Zeta DC-DC Converter employed as Power Factor Correction converter feeding a BLDC (Brush less DC) motor drive is proposed. Zeta DC-DC converter which lies between an uncontrolled bridge rectifier and a dc link capacitor is used to control the voltage of the dc link capacitor. The Brush Less DC motor is fed from a single phase supply. The DC link capacitor is in between the Zeta Converter and a VSI (Voltage Source Inverter). A voltage follower approach is used to control the dc link voltage of the Zeta converter and the converter is working in DCM (Discontinuous Conduction Mode). To eliminate the requirement of Hall Effect position sensors a sensor less control of BLDC motor is used. For this sensor less operation, inverter pulses are generated by back emf estimation of the motor drive. A MATLAB/Simulink environment is used to simulate the model. A wide range of speed control is possible with high PF (Power Factor) and improved PQ(Power Quality) at the ac mains supply.***

Keywords: DCM, PFC, BLDC motor, Zeta, VSI

1. Introduction

The selection of a drive mainly depends on three main factors; efficiency, cost and design simplicity. These factors play an important role for designing a motor drive for household appliances. Other main factor is the requirement of improved power quality at the AC mains as imposed by the international PQ (Power Quality) standards like IEC 61000-3-2[1]. Class D applications require the power factor to be above 0.9 and the THD (Total Harmonic Distortion) less than 5%. This paper deals with the design of such a motor drive with improved power quality at the AC mains for a wide range of speed control. Brush Less DC motors are becoming popular for low and medium power applications because of their high efficiency, high reliability, low maintenance requirements, and low noise levels[2]. BLDC motors are permanent magnet synchronous motors with three phase windings on stator and permanent magnets on the rotor. These are trapezoidal back emf motors with no brushes and commutator assembly. These are electronically commutated motors through a VSI and the rotor position is sensed with the help of hall effect position sensors or by using sensorless methods. Class D applications recommends the use of improved power quality converters for the BLDC motor drive.

Conventional BLDC motors are fed from a combination of diode bridge rectifier and a dc link capacitor followed by a voltage source inverter. This combination draws supply current from a single phase supply which is rich in harmonics and leads to a poor power factor of the order of 0.8 and hence it cannot be used for feeding the BLDC motor drive to attain an improved power quality at the AC mains. Widely used PFC converters require a two stage power conversion in which the first stage is for power factor correction and the second stage for voltage regulation. This two stage topology is more complex and results in more cost and losses and hence a single stage zeta converter is proposed which is used to control the voltage of a dc link capacitor and for power factor correction. The zeta converter is working in discontinuous conduction mode and hence a voltage follower approach is used. In continuous conduction mode a current multiplier approach is used. A sensorless control of BLDC motor is used which eliminate the requirement of Hall Effect position sensors thus making the drive more cost effective.

2. Proposed Speed Control Scheme of Sensorless BLDC Motor Drive

The proposed scheme for the Sensorless BLDC motor drive fed by a Zeta based PFC converter operating in DICM mode is shown in Fig. 1. The front end Zeta DC-DC converter maintains the DC link voltage to a set reference value. Switch of the Zeta converter is to be operated at high switching frequency for effective control and small size of components like inductors. A sensorless approach is used to detect the rotor position for electronic commutation. A blind start up is used for starting the BLDC motor. A high frequency MOSFET of suitable rating is used in the front end converter for its high frequency operation whereas an IGBT's (Insulated Gate Bipolar Transistor) are used in the VSI for low frequency operation.

The proposed scheme maintains high power factor and low THD of the AC source current while controlling rotor speed equal to the set reference speed. A voltage follower approach is used for the control of Zeta DC-DC converter operating in DCM. The DC link voltage is controlled by a single voltage sensor. Vdc (sensed DC link voltage) is compared with Vdc* (reference voltage) to generate an error signal which is the difference of Vdc* and Vdc. The error signal is given to a PI (Proportional Integral) controller to give a controlled output. Finally, the controlled output is compared with the high frequency saw tooth signal to generate PWM (Pulse Width Modulation) pulse for the

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MOSFET of the Zeta converter. A rate limiter is used to limit the stator current during step change in speed.

3. Design of PFC ZETA Converter

The proposed drive system is designed for Zeta converter as PFC converter fed BLDC motor drive operating in DCM.

The output inductor value is selected such that the current remains discontinuous in a single switching cycle. The average input voltage Vin after the rectifier is given as,

$$Vin = 2\sqrt{2}.Vs / \pi \quad (1)$$

where Vs is the rms value of the supply voltage.

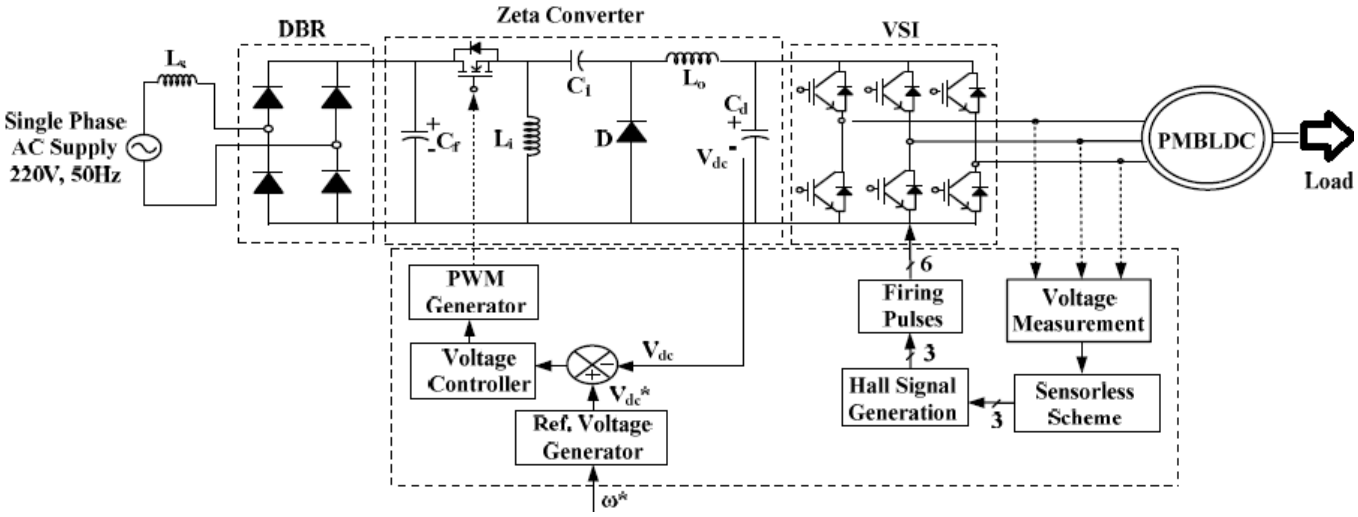


Figure 1: Proposed Zeta converter fed Sensorless BLDC MOTOR drive with voltage follower approach for fan application

The duty ratio D for the Zeta converter (buck-boost) is given as,

$$D = Vdc / (Vin + Vdc) \quad (2)$$

where Vdc represents the DC link voltage of Zeta converter. If the permitted ripple of current in input inductor Li and output inductor Lo is given as ΔiLi and ΔiLo respectively, then the inductor value Li and Lo are given as,

$$Li = D.Vin / \{fs.(\Delta iLi)\} \quad (3)$$

$$Lo = (1-D)\ Vdc / \{fS.(\Delta iLo)\} \quad (4)$$

where fS is the switching frequency.

For the critical conduction mode, ΔiLo = 2.Idc i.e.

$$Lo(critical) = (1-D)\ Vdc / \{fS.\ (2.Idc)\} \quad (5)$$

The value of intermediate capacitor C1 is given as,

$$C1 = D.Idc / \{fs.\ (\Delta VC1)\} \quad (6)$$

where ΔVC1 is the permitted ripple in C1.

The value of DC link capacitor Cd is given as [8-11],

$$Cd = Idc / (2.\omega.\Delta Vdc) \quad (7)$$

where $\omega = 2\pi f_L$; f_L is the line frequency.

Equations (1)-(7) represent the design criteria of the Zeta converter in discontinuous conduction mode.

A PFC converter of rating 500W is designed for operating at 50-200V at source voltage Vs = 220V for switching frequency of 45 kHz. The ripple in input inductor (ΔiLi) current is considered to be 10% and ripple in DC link voltage (ΔVdc) as 4%. The design values thus obtained are Li = 2.463 mH, Lo = 60 µH, C1 = 330 nF and Cd = 2500 µF.

Control of PFC Based ZETA Fed Sensorless Bldc Motor Drive

The PFC converter and the sensorless BLDC motor drive are modeled for the proposed drive scheme. The control scheme of the PFC converter consists of following three blocks.

A. Reference Voltage Generator

The speed of BLDC motor is proportional to the DC link voltage of the VSI, hence a reference voltage generator is required to produce an equivalent voltage corresponding to the particular reference speed of the BLDC motor. The reference voltage generator produces a voltage by multiplying the speed with a constant value known as the voltage constant (Kb) of the BLDC motor.

B. Speed Controller

An error of the Vdc* and Vdc is given to a PI (Proportional Integral) speed controller which generates a controlled output corresponding to the error signal. The error voltage Ve at any instant of time k is as;

$$Ve(k) = Vdc^*(k) - Vdc(k) \quad (8)$$

and the output Vc(k) of the PI controller is given by,

$$Vc(k)=Vc(k-1)+Kp.(Ve(k)-Ve(k-1))+Ki.Ve(k) \quad (9)$$

where Kp is the proportional gain and Ki is the integral gain constant.

C. PWM Generator

The output of the PI controller Vc is given to the PWM generator which produces a PWM signal of fixed frequency and varying duty ratio. A saw tooth waveform is compared

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with the output of PI controller as shown in Fig. 3 and PWM is generated as;

$$\text{If } md(t)<Vc(t) \text{ then } S=1 \text{ else } S=0 \quad (10)$$

where S denotes the switching signals as 1 and 0 for MOSFET to switch on and off respectively.

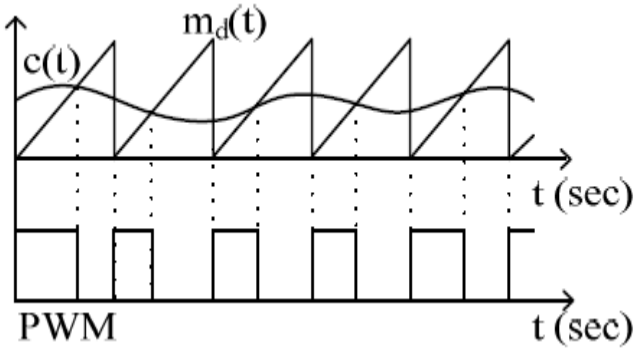


Figure 3: Generation of PWN signal by comparing a saw tooth waveform with the controller output

4. Modelling of Proposed BLDC Motor Drive

The modeling of a BLDC motor drive consists of a modeling of a BLDC motor, a VSI and an electronic commutation using sensorless approach.

A. BLDC Motor

The dynamic modeling of the BLDC motor is governed by the following equations given as [8],

$$Van = Raia + p\lambda a + ean \quad (11)$$
$$Vbn = Rbib + p\lambda b + ebn \quad (12)$$
$$Vcn = Rcic + p\lambda c + ecn \quad (13)$$

where p represents the differential operator, Van, Vbn and Vcn are the per phase voltages, Ra, Rb and Rc are resistances per phase, ia, ib and ic are currents, ean, ebn and ecn represents back emf and λa, λb, and λc represents flux linkages.

Van, Vbn and Vcn is also given as,

Van = Vao – Vno,
Vbn = Vbo – Vno and

$$Vcn = Vco – Vno \quad (14)$$

where Vao, Vbo, Vco are the three phase voltages and Vno is the neutral voltage referred to the zero reference potential as shown in Fig. 4. The flux linkages are given as,

$$\lambda a = Lsia – M(ib+ic) \quad (15)$$
$$\lambda b = Lsib – M(ia+ic) \quad (16)$$
$$\lambda c = Lsic – M(ia+ib) \quad (17)$$

where Ls is the self inductance per phase and M is the mutual inductance of the windings. Moreover for star connected three phase windings of the stator,

$$ia+ib+ic = 0 \quad (18)$$

The flux linkages can be expressed as,

$$\lambda x = (Ls + M).ix \quad (19)$$

where x denotes a, b or c (i.e. phase terminals).

The generalized equation by using equations (11)-(13) and (18),

$$pix = (Vxn – ixRx – exn)/(Ls+M) \quad (20)$$

The developed electromagnetic torque is expressed as,

$$Te = (ean\ ia + ebn\ ib + ecn\ ic)/\omega r \quad (21)$$

where ωr is the rotor speed in electrical rad/sec.

This expression for the torque faces computational difficulty at zero speed as induced emf's are zero. Hence, it is reformulated by expressing back-emf as a function of position Θ, which can be written as,

$$ean = kbfa(\Theta)\omega r \quad (22)$$
$$ebn = kbfb(\Theta)\omega r \quad (23)$$
$$ecn = kbfc(\Theta)\omega r \quad (24)$$

Substituting equations (22)-(24) into equation (21), the torque expression becomes,

$$Te = kb\{fa(\Theta)\ ia + fb(\Theta)\ ib + fc(\Theta)\ ic\} \quad (25)$$

where kb is the back emf constant and fa(Θ), fb(Θ) and fc(Θ) are rotor position function having a maximum magnitude of plus or minus 1 and is given as,

$$fa(\Theta) = 1; \text{ for } 0<\Theta<120° \quad (26)$$
$$fa(\Theta) = \{(6/\pi)(\pi-\Theta)\}-1; \text{ for } 120°<\Theta<180° \quad (27)$$
$$fa(\Theta) = -1; \text{ for } 180°<\Theta<300° \quad (28)$$
$$fa(\Theta) = \{(6/\pi)(\pi-2\Theta)\}+1; \text{ for } 300°<\Theta<360° \quad (29)$$

The functions for b and c phase can be calculated by using a 120° and 240° phase difference respectively. The torque balance equation is given as,

$$Te = TL + B\omega r + J.\ (2/P).d\omega r/dt \quad (30)$$

where Te is developed electromagnetic torque, TL is load torque, B represents the frictional coefficient in Nms/rad, P is the number of poles and J represents the moment of inertia in kg-m2.

The potential of neutral terminal with respect to zero potential (Vno) is required to be considered in order to avoid unbalance in applied voltage. Substituting equation (14) in equation (11) to (13) and adding them together gives,

$$Vao + Vbo + Vco – 3Vno = R(ia + ib + ic) + (Ls+M)(pia + pib + pic) + (ean + ebn + ecn) \quad (31)$$

Substituting equation (18) in equation (31) one gets,

$$Vao + Vbo + Vco – 3Vno = (ean + ebn + ecn) \quad (32)$$

$$\text{Thus, } Vno = \{Vao + Vbo + Vco - (ean + ebn + ecn)\}/3 \quad (33)$$

A dynamic model of a BLDC motor is represented in equations (11)-(33).

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B. Voltage Source Inverter

The output of the VSI for phase 'a' is expressed as,

$$Van = Vdc / 2 \text{ for } S1=1; \quad (34)$$
$$Van = -Vdc / 2 \text{ for } S2=1; \quad (35)$$
$$Van = 0 \text{ for } S1=0, S2=0; \quad (36)$$

where Vdc is the DC link voltage and the values for S1 and S2 as 1 and 0 represent the on and off condition of the IGBT's S1 and S2. When switch S1 and S4 are on then phase 'a' and 'b' are connected and the current ia (ia = ib) flows through the motor windings and the third phase 'c' remains in floating condition as shown in Fig. 4.

The equation for line voltage Vab is given as,

$$Vab = Vdc = Ra + La\, dia/dt + ean + Rb + Lb\, dib/dt + ebn \quad (37)$$

If La = Lb = L, Ra = Rb = R, ia =ib and eab = ea + eb then,

$$Vdc = 2.R.ia + 2\, L.dia/dt + eab \quad (38)$$

where ia is the line current (or the phase current) of the motor. Similarly the other combination of switches can be obtained.

C. Electronic Commutation

The switching sequence of VSI for different positions of the rotor as estimated by sensorless scheme.

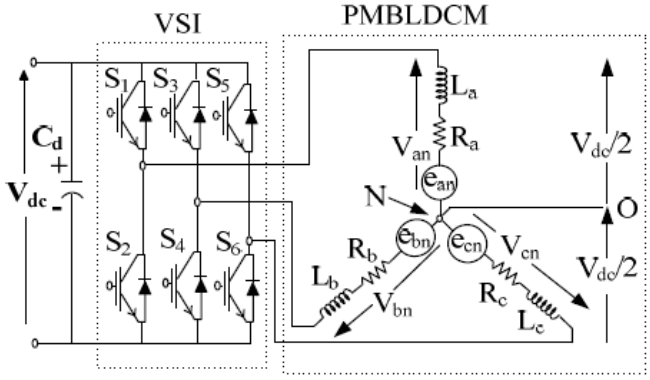


Figure 4: Equivalent circuit of BLDC motor fed by a VSI

5. Sensorless Operation of BLDC Motor Drive

To eliminate the requirement of Hall Effect position sensors for the overall cost reduction of the PFC drive system, a sensorless approach is used. Many sensorless techniques are available in the literature for the estimation of position of the rotor [12]. In this paper, line back emf is used for position detection using a ZCD (Zero Crossing Detector). The complete operation of sensorless BLDC motor is classified into open loop starting, switching from starting to sensorless mode and finally the sensorless operation.

A. Open Loop Starting

In open loop startup technique, a rotating field at the stator is given with gradually increasing magnitude and frequency such that it can overcome the rotor inertia and friction at standstill position and begins rotating at low speed. The voltage applied should be such that the current should not exceed the maximum current rating of the BLDC motor.

B. Switching from Starting to Sensorless Mode

When the rotor rotates above a certain speed in the open loop starting, and proper estimation of the virtual Hall Effect position signals are obtained then the motor is switched from open loop starting mode to sensorless mode of operation.

C. Sensorless Operation

There are numerous methods for the estimation of rotor position [12, 13]. A basic approach of determining line voltage is by the measurement of phase voltage with the virtual ground and then calculating the line voltage is used. A ZCD detects the zero crossing of the voltage and then the virtual Hall signals for electronic commutation are generated. Fig. 6 shows the starting, switching from starting to sensorless mode and the sensorless operation of the BLDC motor drive. As shown in this figure the estimated virtual Hall Effect rotor position signal and the actual hall signals are overlapping showing the accurate detection of position using the sensorless algorithm. Moreover, the stator current is much less than the maximum current rating of motor during open loop starting and a smooth transition from open loop starting to sensorless mode is also achieved.

6. Performance Evaluation

The proposed model is simulated in MATLAB/Simulink environment for a 500W sensorless BLDC motor drive system for fan application. The fan load is considered as load proportional to the square of speed, so at very low speed the load torque on the motor is very less and as the speed increases the load torque increases rapidly. Parameters like THD, CF (crest Factor), DPF (Displacement Power Factor) and PF at the AC mains of the proposed PFC drive are used for performance evaluation. The detailed specifications of the motor are mentioned in Appendix. Table I shows the steady state performance evaluation parameters at speed control of the Zeta converter fed Sensorless BLDC motor drive. A satisfactory performance is achieved over a wide speed range with improved power quality at the AC mains. The THD is maintained below 5% and power factor near unity for a wide range of speed control following IEC 61000-3-2 standard. Fig. 8 shows the various parameters of the front end converter and the BLDC motor in steady state at near rated speed. The voltage and current stress on the switch is 600V and 40A respectively as shown in Fig. 8 The DC link voltage is changed from 100V to 200V and a smooth transition with low amount of transients is obtained.

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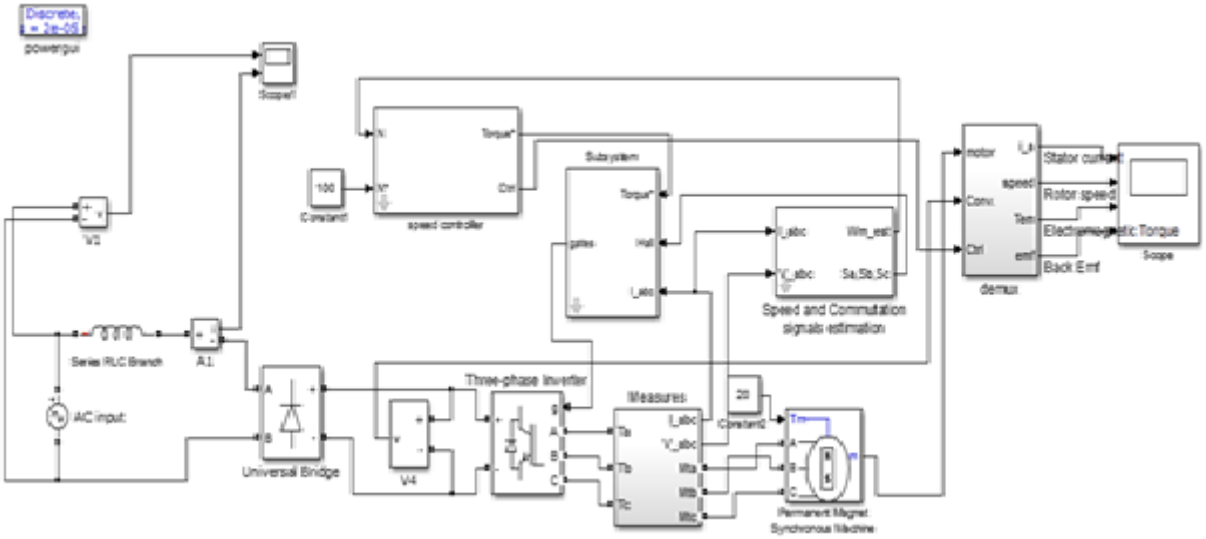


Figure 5: Sensorless BLDC MATLAB/Simulink model

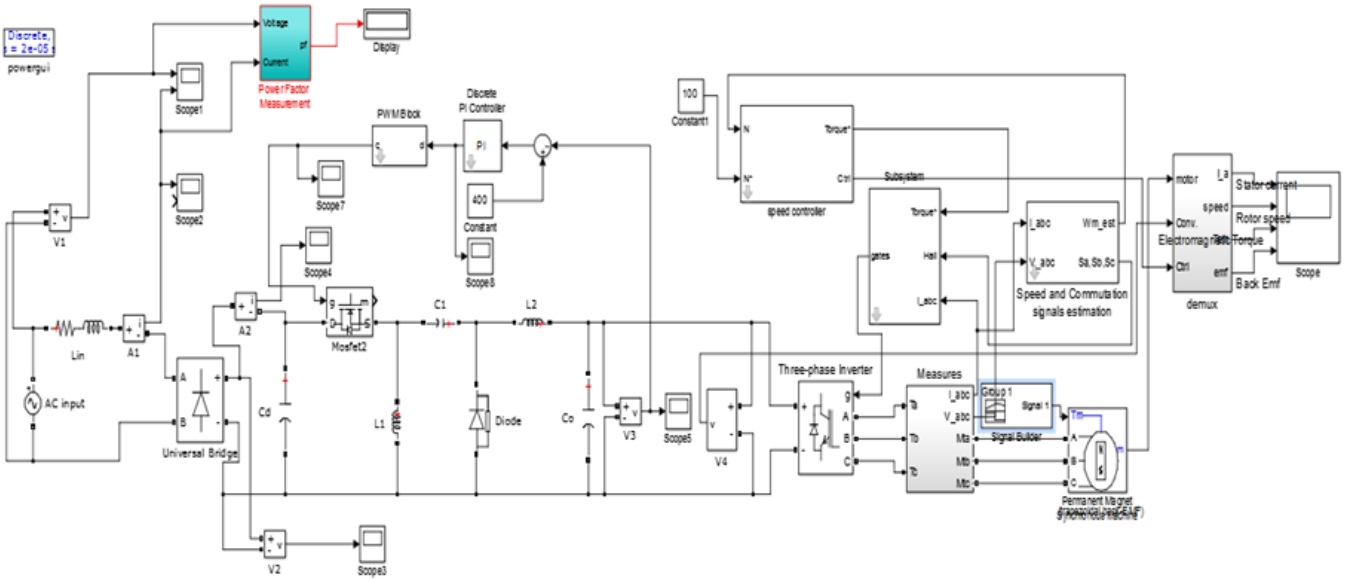


Figure 6: MATLAB model of zeta converter fed BLDC motor drive

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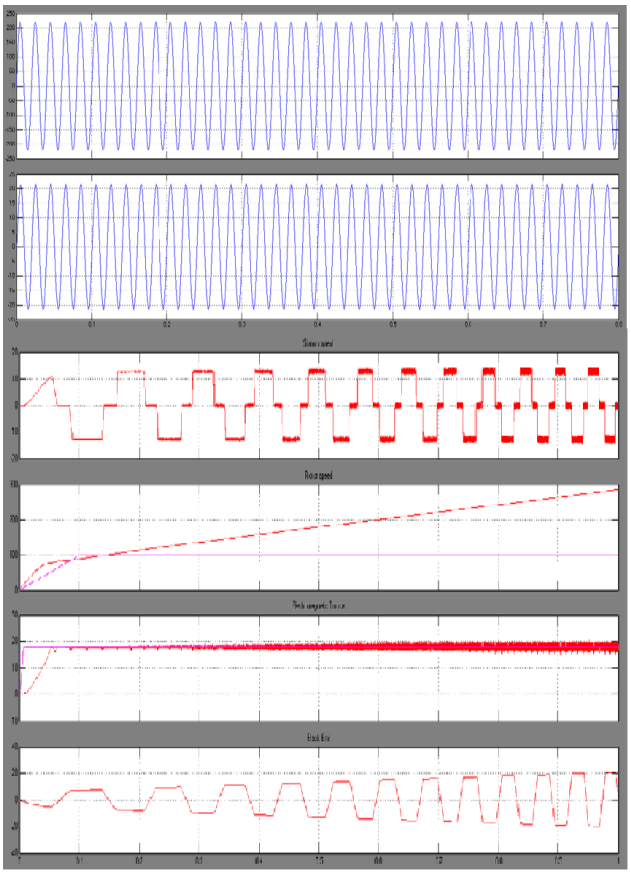


Figure 7: Steady state performance of Zeta converter fed BLDC motor drive working in discontinuous conduction mode:supply voltage,supply current,stator current,rotor speed,torque,back emf.

Table 1: Power Quality Parameters With Input Ac Voltage Variation For Zeta Converter Fed Bldc Motor Drive

Vs	THD of Is	Is	PF	Crest factor
170	1	3.6	0.9888	1.4142
180	1.3	3.5	0.9889	1.4149
190	1.7	3.2	0.9891	1.4193
200	1.9	3	0.9894	1.4172
210	2.1	2.8	0.9893	1.4165
220	2.8	2.7	0.9897	1.4132
230	2.9	2.55	0.9901	1.4155
240	3	2.35	0.9906	1.4169
250	3.1	2.25	0.9912	1.4178
260	3.2	2.2	0.9915	1.4188
270	3.5	2	0.9921	1.4198

Fig. 9 shows the harmonic spectrum of the supply current at near rated speed and the THD obtained as 3.8% which is well below the international PQ standards limits. The performance of BLDC motor drive on the variation of supply voltage is tabulated in Table I to demonstrate that the proposed PFC converter operates satisfactorily in the practical situation. The THD of supply current is controlled within 5% with near unity power factor operation.

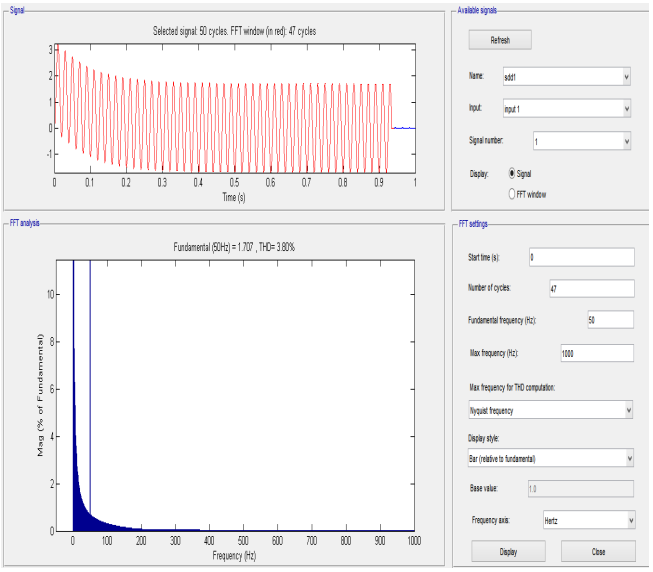


Figure 8: The harmonic spectrum of the supply current at near rated speed

7. Conclusion and Future Scope

A simple control using a voltage follower approach has been used for voltage control and power factor correction of a PFC Zeta converter fed BLDC motor drive. A novel scheme of speed control using a single voltage sensor has been proposed for a fan load. A sensorless operation for the further reduction of position sensor has been used. A single stage PFC converter system has been designed and validated for the speed control with improved power quality at the AC mains for a wide range of speed. The performance of the proposed drive system has also been evaluated for varying input AC voltages and found satisfactory. The power quality indices for the speed control and supply voltage variation have been obtained within the limits by International power quality standard IEC 61000-3-2. The proposed drive system has been found a suitable candidate among various adjustable speed drives for many low power applications. As a future expansion, we will be going for a hardware implementation of the work.

8. Appendix

BLDC Motor Rating: 4 pole, Prated (Rated Power) = 424.11W, Trated (Rated Torque) = 1.35 Nm, ωrated (Rated Speed) = 3000 rpm, Kb (Back EMF Constant) = 51 V/krpm, Kt (Torque Constant) = 0.49 Nm/A, Rph (Phase Resistance) = 7.20Ω, L (Phase Inductance) = 4.77 mH, J (Moment of Inertia) = 0.37 kg-cm2.

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