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

P SIDDARTHA
M-tech Student Scholar
Department of Electrical & Electronics Engineering, Anurag College of Engineering (Formerly CVSR college of Engineering), Ghatkesar (M); Medchal (D); Telangana, India.

B NAGESWARA RAO
Associate Professor
Department of Electrical & Electronics Engineering, Anurag College of Engineering (Formerly CVSR college of Engineering), Ghatkesar (M); Medchal (D); Telangana, India.

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 change in the current sources 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 simple 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.

**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 (Vdc) 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

\[
V_S(t) = V_m \sin(\omega t) = 220/\sqrt{2} \sin(314t) V
\]

where \(V_m\) is peak input voltage (i.e., √2 VS) and \(\omega L = 2\pi fL\); \(fL\) is the line frequency, i.e., 50 Hz.

**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.

---

Available online: [https://edupediapublications.org/journals/index.php/IJR/](https://edupediapublications.org/journals/index.php/IJR/)
The instantaneous output voltage of DBR is given as
\[ V_{B}(t) = |V_m \sin(2\pi f_s t)| = 220\sqrt{2} \sin(314t) \] V
(2)

where \( \text{mod} \) represents the modulus function. The output voltage \( V_{dc} \) of an isolated zeta converter which belongs to a buck-boost category is given as [7]

\[ V_{dc} = \left( \frac{N_2}{N_1} \right) \frac{D}{(1 - D)} V_m \] (3)

where \( D \) represents the duty ratio and \( N_2/N_1 \) 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 \( V_{in}(t) \) and required dc link voltage \( V_{dc} \). An instantaneous duty ratio \( D(t) \) is obtained by substituting (2) in (3) and rearranging it as

\[ D(t) = \frac{V_k - V_{in}(t)}{V_k - V_{dc}(t)} = \frac{\frac{1}{2} V_k}{V_k - V_{in}(t)} - \frac{V_{in}(t)}{V_k} \] (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

\[ P_i = \left( \frac{P_{max}}{V_{dc_{max}}} \right) V_{dc} \] (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 as 115 W. The critical value of magnetizing inductance of the HFT \( L_{mc} \) is expressed as [13]

\[ L_{mc} = \frac{R_L f_s}{2D(t)(\frac{N_2}{N_1})^2} \left( \frac{V_k^2}{P_i} \right) \frac{(1 - D(t))^2}{2D(t)(\frac{N_2}{N_1})^2} \] (6)

where \( R_L \) represents the emulated load resistance, \( f_s \) is the switching frequency (which is taken as 20 kHz), and \( P_i \) is the instantaneous power. The critical value of magnetizing inductance \( L_{mc} \) 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 limiter, 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

\[ V_{dc}^* = k_v \omega^* . \]  \hspace{1cm} (16)

The “voltage error generator” compares this reference dc link voltage (Vdc*) with the sensed dc link voltage (Vdc) to generate an error voltage (Ve) given as

\[ V_e(k) = V_{dc}(k)^* - V_{dc}(k) \]  \hspace{1cm} (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

\[ V_{cc}(k) = V_{cc}(k-1) + K_p [V_e(k) - V_e(k-1)] + K_i V_e(k) \]  \hspace{1cm} (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

\[ \begin{cases} 
\text{if} \ m_d < V_{cc}, \text{then} & S_w = \text{“ON”} \\
\text{if} \ m_d > V_{cc}, \text{then} & S_w = \text{“OFF”} 
\end{cases} \]  \hspace{1cm} (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 (eab 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.

VLINTRODUCTION 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 defuzzification interface which yields non-fuzzy control action from an inferred fuzzy control action [10].
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>
<thead>
<tr>
<th>e (e)</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>ZO</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>NM</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
</tr>
<tr>
<td>NS</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PS</td>
<td>PM</td>
</tr>
<tr>
<td>ZO</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>PM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>de</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>ZO</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>NM</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>ZO</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>NS</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>ZO</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>PS</td>
<td>NM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>PM</td>
<td>NS</td>
<td>ZO</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>PB</td>
<td>ZO</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

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
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.

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.

REFERENCES
AUTHOR’S PROFILE:

P. SIDDARTH received B.Tech from Geethanjali College of Engineering and Technology Keesara, in the year 2012 and now pursuing M.Tech in the stream of Power Electronics and Electrical Drives at Anurag Group of Institutions (Formerly Known as CVSR College of Engineering), Ghatkesar, Medchal Dist, Telangana. His areas of interests are Electrical Machines, Power Electronics and Power systems.

B. NAGESWARA RAO working as Assistant Professor in Anurag Group of Institutions (Formerly known as CVSR College of Engineering), Jodimetla, Venkatapuram, Ghatkesar (m), Medchal (Dist), Telangana. Diploma in EEE Vasavi Polytechnic, Kurnool (dist), AP, B.Tech in EEE ACET Hyderabad, M.tech in Power Electronics R.G.M. College of Engg (Panyam) JNTUA. Teaching Experience 7 years, Areas of Interest Power Electronics, Power systems, Electrical machines & Drives, Published Papers 7 international Journals till date.