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Comparison on Performance between PI and Fuzzy Controlled Zeta Converter in BLDC Motor Drive

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Abstract: ***Due to high efficiency, silent operation, compact size, high reliability, ease of control, and low maintenance requirements the brushless DC motor (BLDCM) drives are being employed in many variable speed applications . This paper present a comprehensive analysis of power factor correction (PFC) zeta converter fed brushless dc motor drive with PI and fuzzy controller. The brushless dc motor drives have poor power factor and power quality problems at input AC mains as they are mostly fed through diode bridge rectifier based voltage source inverters. In this work, the speed of the BLDC motor is controlled by adjusting the dc link voltage of the voltage source inverter (VSI) feeding a BLDC motor. This thesis deals with the implementation of pulse width modulated Zeta converter with better efficiency, lower total harmonic distortion factor and power factor correction. The proposed drive is implemented to achieve a unity power factor at ac mains for a wide range of speed control and supply voltage fluctuations. A MATLAB/ Simulink environment is used to simulate the model to achieve a wide range of speed control with improved PQ (Power Quality) at the supply.***

Keywords: BLDC (Brushless direct current), PQ (Power Quality), PFC (Power Factor Correction), VSI (Voltage Source Inverter), PI (Proportional Integral)

1. Introduction

In recent years brushless dc (BLDC) motors are widely used applications including appliances, automotive, aerospace, consumer, medical, automated industrial equipment and instrumentation because of their high starting torque, high efficiency, reliability, lower maintenance compared to its brushed dc motor. In a BLDC motor, the rotor magnets generate the magnetic flux, so BLDC motors achieve higher efficiency. [1] [2] Therefore, BLDC motors may be used in high end white goods (refrigerators, washing machines, dishwashers, etc.), high-end fans, and pumps and in other appliances which require high reliability and efficiency.

The BLDC motors have many advantages over brushed DC motors and induction motors, like higher efficiency and reliability, lower acoustic noise, smaller and lighter, greater dynamic response, better speed versus torque characteristics, higher speed range, longer life. Since the specific torque is higher it can be very useful in the applications were space and weight are critical factors. And also the BLDC motor is electrically commutated by power switches instead of brushes it has so many advantages such as no brushes/commutator maintenance, no brush friction to reduce useful torque, no mechanical limitation imposed by brushes or commutator, no arcs from brushes to generate noise, causing EMI problems.[3]

The BLDC motor drive is fed from single-phase ac supply through a diode bridge rectifier (DBR) followed by a high value of smoothening capacitor at dc link which draws a pulsed current, with a peak higher than the amplitude of the fundamental input current at ac mains due to an uncontrolled charging and discharging of the dc link capacitor.[4] This causes in poor power quality (PQ) at ac mains in terms of poor power factor (PF), high total harmonic distortion (THD) of ac mains current, and high crest factor (CF). Therefore, a Power Factor correction (PFC) converter is inevitable for Brushless DC Motor Drive to improve the power quality. [5]

There are many existing topologies regarding power factor correction in BLDC motor drive. Some of the existing topologies consist of a Single Ended Primary Inductance Converter (SEPIC) and buck-boost converter based BLDC motor drive which has higher losses in the voltage source inverter due to conventional PWM switching and large number of voltage and current sensors are used that additionally adds to the cost of the converter. And in another topology a cuk converter fed BLDC motor drive with a variable DC link voltage is used that reduces the switching losses since it uses only the fundamental switching frequency, but it has a major disadvantage that it requires three sensors. So it is not used for low power rating and low-cost applications.[6]-[8] The above used topologies consist of bridge converters and it also contributes switching losses so bridgeless topologies are preferred. The usage of diode rectifiers that cause more switching stresses are eliminated by bridgeless converters.[9] And also some topologies with bridgeless converters like bridgeless boost, cuk, buck-boost, SEPIC converters are there. But all these power factor correction techniques have some limitations. They cannot be used for low power applications.[10] So the proposed PFC technique below is designed in such a way that is suited for low power applications.[11]-[14]

The objective of the paper is to use zeta converter fed BLDC motor drive inorder to improve the power quality at the supply by reducing the total harmonic distortion factor and increasing power factor to unity. And also by adjusting the dc link voltage of the voltage source inverter (VSI) feeding a BLDC motor, the speed of the BLDC motor is controlled.

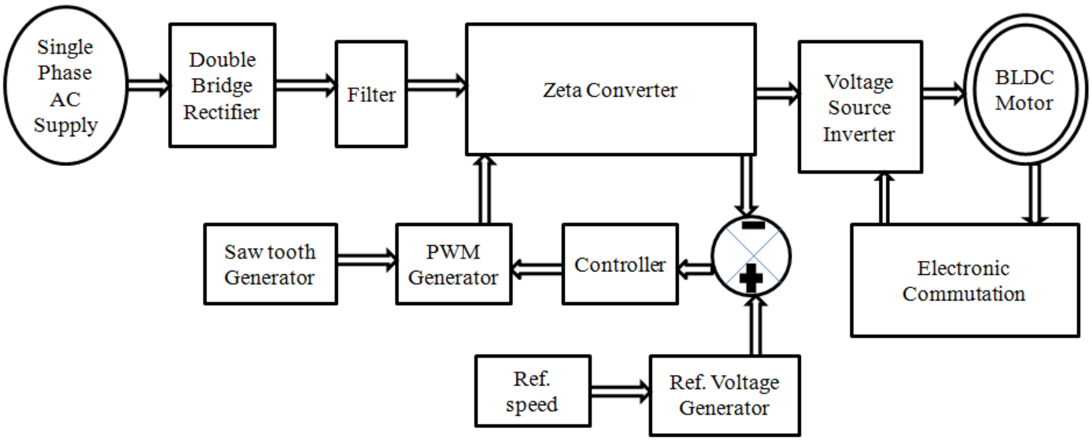

Figure 1: Proposed PFC-based zeta converter fed BLDC motor drive

2. Proposed PFC-Based BLDC Motor Drive with Zeta Converter

Fig.1 shows the proposed zeta converter-fed BLDC motor drive. A single-phase ac supply is converted to DC by using DBR followed by a large value capacitive filter and zeta converter. The filter is is used to reduce DC voltage ripples, which produces an increased THD of input AC mains current and excessive peak input currents that leads to poor power factor. The zeta converter is designed to operate in DCM to act as an inherent power factor correction converter. This combination of DBR and PFC zeta converter is used to feed a BLDC motor drive through a three-phase VSI as shown in Fig. 1. The speed of BLDC motor is directly proportional to the DC link voltage of the VSI. The reference voltage generator produces a voltage by multiplying the speed with the voltage constant (Kb) of the BLDC motor drive. An error voltage obtained by comparing the measured dc link voltage and reference voltage is fed to PI controller. The Proportional Integral controller is used to minimize the error signal and also it produce a controlled output to the PWM generator to produce a PWM signal of fixed frequency and varying duty ratio.

2.1 Operation of Zeta Converter

This converter is the latest type of single-stage input current shapers. It also uses single switching device and inherently provides an overload, short circuit, and inrush current protections. Since zeta converters behave as a resistive load to input AC mains, this converters are also called resistance emulators. Zeta converter is fourth order converters that can step down or step up the input voltage. The ZETA converter also have a series capacitor sometimes called a flying capacitor and two inductors. The ZETA converter topology gives a positive output voltage from an input voltage.

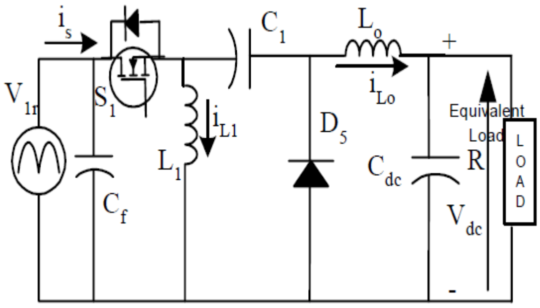

Figure 2: Circuit of Zeta Converter

The Zeta converter has many advantages, such as buck-boost capability, and continuous output current, input to output DC insulation, so it can be used in high reliability system. This topology offer high efficiency, especially by using the synchronous rectification. The synchronous rectification can be easily implemented in this converter, because this topology, unlike the SEPIC converter, uses a low-side rectifier. The equivalent circuit of the Zeta converter is shown in Fig.2

2.1 Design of Zeta Converter

The design of zeta converter for power factor correction and speed controlled in BLDC motor drive has the main objective of the PQ improvement at AC mains. The design equations of zeta converter are given below.
The expression for output DC Link Voltage of zeta converter

$$V_d = \left(\frac{n_2}{n_1}\right) V_i \frac{D}{(1-D)} \quad (1)$$

where V_i is the input voltage applied to zeta converter

$$V_i = \frac{2\sqrt{2}}{\pi} V_s \quad (2)$$

The Critical value of Magnetizing Inductor is expressed as

$$L_m = \left(\frac{V_d^2}{P_i}\right) \frac{\{1-D\}}{2D\, f_s \left(\frac{n_2}{n}\right)^2} \quad (3)$$

where D represents the duty ratio and $n2/n1$ is the turns ratio of the HFT. the value of L_l is selected around $1/10^{th}$ of L_m and f_s is the switching frequency (which is taken as 20 kHz)

The expression for calculation of output inductor is

$$L_o = \frac{V_{dc}\{1-D\}}{f_s(k\,I_o)} \tag{4}$$

where k represents the percentage ripple of the output inductor current which is taken as 40% of output inductor current. An expression for intermediate capacitor (C1) is as

$$C_1 = \frac{V_{dc}\,D}{\eta\{\sqrt{2}V_s + V_{dc}\}f_s}\left(\frac{P_i}{V_{dc}^2}\right) \tag{5}$$

where P_i is the instantaneous power and η is the permitted ripple voltage across intermediate capacitor.
The value of DC link Capacitor is

$$C_d = \left(\frac{P}{V_{dc}}\right)\frac{1}{2\,\omega(\eta V_{dc})} \tag{6}$$

3. Control of Zeta Converter-fed BLDC Motor Drive

The control of the proposed PFC zeta converter-based BLDC motor drive is divided into two categories: control of PFC zeta converter for dc link voltage control and control of three-phase VSI for electronic commutation of BLDC motor.

3.1 Control of PFC Converter

A voltage-follower approach is used for the control of zeta converter. This control scheme consists of a reference voltage generator, voltage error generator, PI controller, and a PWM generator. A "reference voltage generator" generates a reference voltage V_{dc} by multiplying the reference speed of BLDC motor (ω) with the voltage constant (k_b) of motor as

$$V_{dc} = k_b * \omega \tag{7}$$

The "voltage error generator" compares the reference dc link voltage (V_{dc}) from reference voltage generator with the measured dc link voltage (V^*_{dc}) to generate an error voltage (V_e) given as

$$V_e(k) = V_{dc}^*(k) - V_{dc}(k) \tag{8}$$

where "k" represents the k^{th} sampling instance. This error voltage V_e is given to a PI (proportional integral) controller to generate a controlled output voltage (V_{cc}) to PWM generator which is expressed as

$$V_{cc}(k) = V_{cc}(k-1) + K_p\{V_e(k) - V_e(k-1)\} + K_i V_e(k) \tag{9}$$

where K_p and K_i are the proportional and integral gains of the PI controller. Finally, the PWM signal for switch S_w is generated by comparing the output of PI controller (V_{cc}) with high-frequency saw-tooth signal (m_c) given as

if $m_c < V_{cc}$, then S_w = "*ON*"
if $m_c > V_{cc}$, then S_w = "*OFF*"

where S_w represents the gate signal to PFC converter switch.

3.2 Control of BLDC Motor

An electronic commutation of BLDC motor includes proper switching of voltage source inverter 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 absolute rotor position on a span of 60◦; which is required for the electronic commutation of BLDC motor. When two switches of voltage source inverter, i.e., S_1 and S_4 are in conduction states, a line current i_{ab} is drawn from the dc link capacitor whose magnitude depends on the dc link voltage (V_{dc}), resistances (R_a and R_b), back EMF's (e_{an} and e_{bn}), and self and mutual inductances (L_a, L_b, and M) of stator windings. This current produces the electromagnetic torque (T_e) which in turn increases the speed of the BLDC motor. TABLE I shows switching states of VSI feeding bldc motor based on hall effect position signals.

Table 1: Switching States of VSI Feeding BLDC Motor Based On Hall Effect Position Signals

$\theta(^0)$	Hall Signals			Switching States					
	H_a	H_b	H_c	S_1	S_2	S_3	S_4	S_5	S_6
NA	0	0	0	0	0	0	0	0	0
0-60	0	0	1	1	0	0	0	0	1
60-120	0	1	0	0	1	1	0	0	0
120-180	0	1	1	0	0	1	0	0	1
180-240	1	0	0	0	0	0	1	1	0
240-300	1	0	1	1	0	0	1	0	0
300-360	1	1	0	0	1	0	0	1	0
NA	1	1	1	0	0	0	0	0	0

4. Introduction to Fuzzy Logic Controller

Fuzzy set theory is widely used in the control area with some applications to dc-to-dc converter system. A simple fuzzy logic controller is made up by a group of rules based on the human knowledge regarding the system behaviour. Matlab/Simulink simulation model is built to study the performance of proposed controllers and dynamic behaviour of dc-to-dc converter. The fuzzy logic controller has the ability to improve the robustness of dc-to-dc converters. A Fuzzy Logic controller forms an integral part of controller which processes the error resulting from the comparison of the voltage reference and sensed voltage at DC link. The resultant voltage error is compared with a saw-tooth carrier wave of fixed frequency (f_s) for generating the PWM pulses for controlling switch of PFC converter.

4.1 Fuzzy Logic Rules

The objective of this dissertation is to control the output voltage of the PFC zeta converter. The error and change of error of the output voltage will be the two inputs of fuzzy logic controller. These two inputs are divided into five groups; *NB*: Negative Big, *NM*: Negative Medium, *NS*: Negative Small, *ZO*: Zero Area, *PS*: Positive small, *PM*: Positive Medium and *PB*: Positive Big . These fuzzy control rules for error and change of error is shown in Table II.

Table 2: Fuzzy Rule Table

C / dc	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	Z
NM	PB	PM	PM	PS	PS	Z	NS
NS	PM	PM	PS	PS	Z	NS	NS
Z	PM	PS	PS	Z	NS	NS	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NS	NM	NM	NB
PB	Z	NS	NS	NM	NM	NB	NB

5. Simulation Results

MATLAB software is used to evaluate the effectiveness of PI and Fuzzy controller in BLDC Motor Drive. Simulation parameters of BLDC Motor Drive are given Table III.

Table 3: Specifications of BLDCMD

No. of poles	4
Rated DC bus voltage	130V
Rated Speed	1500rpm
Rated Torque	1.2Nm
Rated Power	188.49W
Voltage Constant	57.59V
Torque Constant	0.55 Nm/A
Stator windings per phase resistance	4.32

5.1 Without Zeta Converter

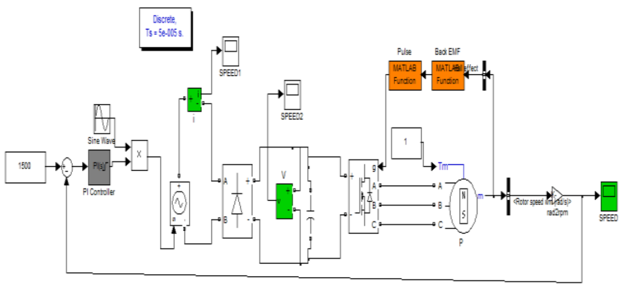

Figure 3: BLDC motor drive without PFC Converter

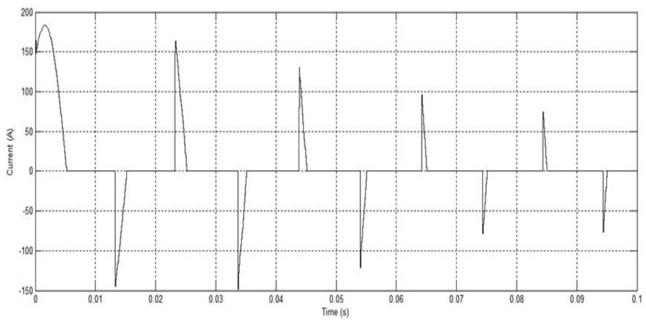

Figure 4: Current waveform at ac mains of BLDCMD without PFC converter

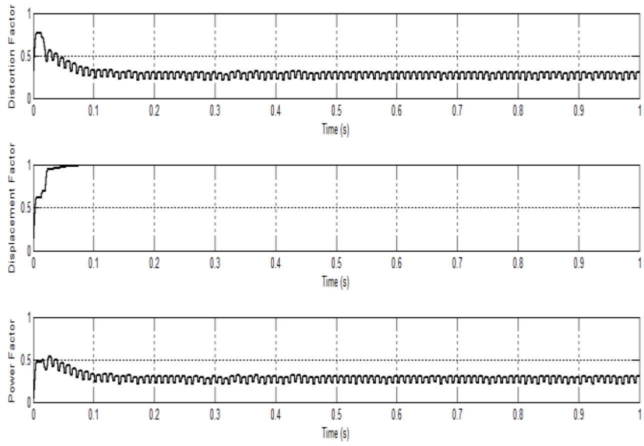

Figure 5: Power factor analysis of BLDC Motor Drive without PFC converters (showing Distortion factor, Displacement factor and Total Power factor)

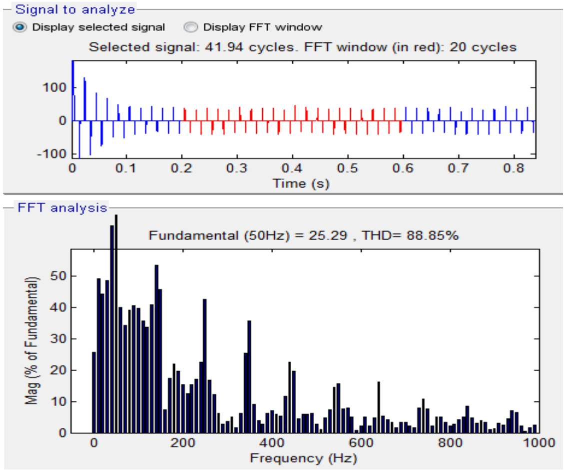

Figure 6: Harmonic Spectra of BLDC Motor Drive without PFC converters

The BLDCMD is fed from a single-phase ac supply through a diode bridge rectifier (DBR) followed by a capacitor at dc link. It draws a pulsed current as shown in Fig. 4, with a peak higher than the amplitude of the fundamental input current at ac mains due to an uncontrolled charging of the dc link capacitor. And fig.5 shows the power factor analysis of BLDC Motor Drive without power factor correction converter. This results in poor power quality (PQ) at ac mains, high total harmonic distortion (THD) of ac mains current (shown in fig. 6) at the value of 88.85%.

5.2 With Zeta Converter

Table 3: Specifications Of BLDCMD

Magnetizing inductance of HFT (L_m)	250 µH
Output inductor (L_o)	4.2 mH
Intermediate capacitor (C_1)	0.44 µF
dc link capacitor (C_d)	2200 µF
filter capacitor (C_f)	330 nF
filter inductor (L_f)	3.77mH

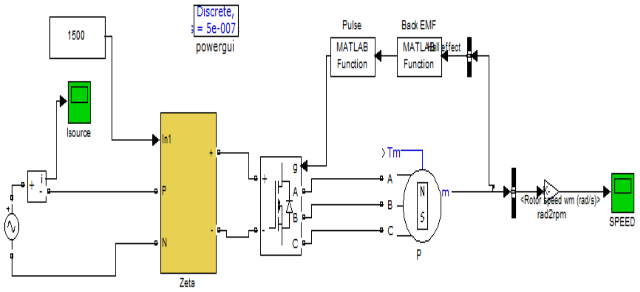

Figure 7: BLDC Motor Drive with Zeta converter

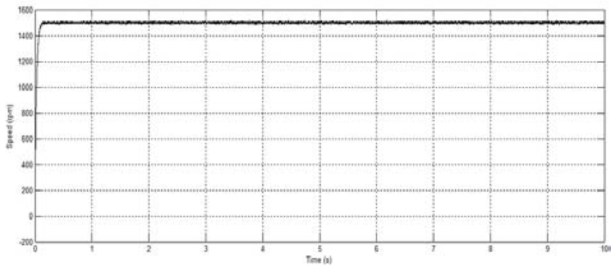

Figure 8: Speed Control of BLDC Motor Drive with Zeta converter

Fig 8 shows the speed control of BLDC motor at reference speed of 1500 rpm, the speed of the BLDC motor is controlled by adjusting the dc link voltage of the voltage source inverter (VSI) feeding a BLDC motor.

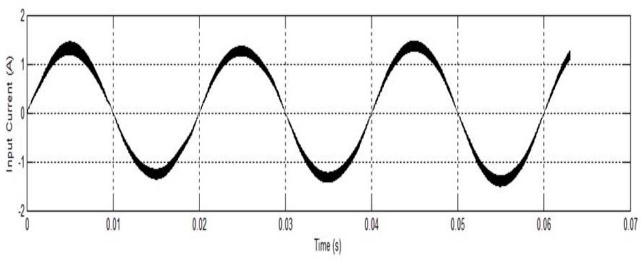

Figure 9: Current waveform at ac mains of Zeta Converter fed BLDC Motor Drive

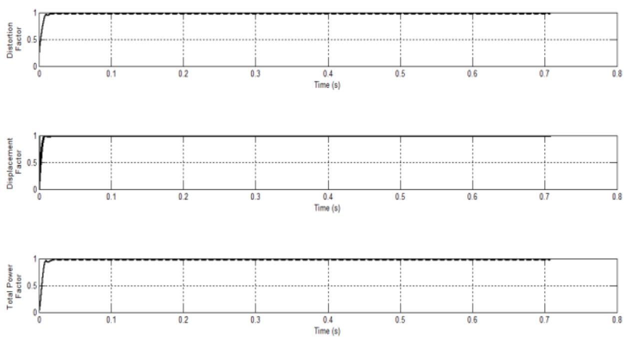

Figure 10: Power factor analysis of BLDC Motor Drive with PFC converters (showing Distortion factor, Displacement factor and Total Power factor)

The current waveform at ac mains with zeta converter is as shown in Fig.9. And Fig.10 also shows the power factor analysis of BLDC Motor Drive with zeta converter.

5.2.1 PI Controlled Zeta Converter

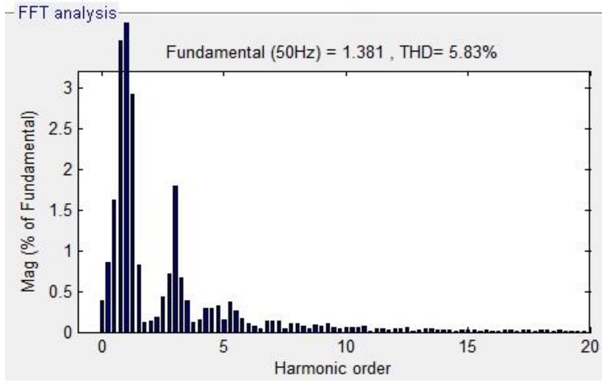

Figure 11: Current Harmonic Spectra of BLDC Motor Drive with PI controlled zeta converter

Due to the presence of PI controlled zeta converter in BLDC motor drive the total harmonic distortion has been reduced to 5.83% which is shown in the Fig.11.

5.2.2 Fuzzy Controlled Zeta Converter

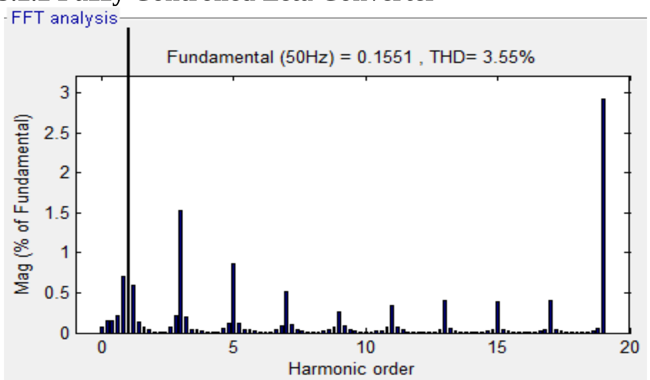

Figure 12: Current Harmonic Spectra of BLDC Motor Drive with Fuzzy controlled zeta converter

And by using Fuzzy controlled zeta converter the power quality is again improved by reducing the THD value to 3.55% (shown in Fig.12).

5.3 Inference

Table 4: Performance Comparison

System Configuration of BLDC Motor Drive	*THD Value*
Without PFC Converter	88.85 %
PI Controlled Zeta Converter	5.83 %
Fuzzy Controlled Zeta Converter	3.55 %

The TABLE IV shows the performance comparison of PI controlled and Fuzzy controlled zeta converter fed BLDC Motor Drive.

6. Conclusion

A fuzzy controlled 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. An 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. The simulated results shows improved performance of the proposed Zeta converter fed BLDC Motor drive in terms of high power factor at supply current and improved power quality at the AC mains.

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