A FUZZY LOGIC APPROACH TO IMPROVE POWER QUALITY IN SINGLE-PHASE AC–DC ZETA

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Abstract–The rapid development in power electronic systems, driven by the use of power semiconductor devices, has led to their application across a wide range of sectors including residential, commercial, aerospace, and more. However, power converters are a major source of **harmonic distortion** and **low power factor** in power systems, which remains a key concern. The conventional single-phase AC–DC conversion method using a diode bridge and bulk capacitor presents several drawbacks, such as injection of low-order harmonics into the AC supply, poor power factor, high peak current, distortion of line voltage, increased electromagnetic interference, and additional power losses.

This study focuses on evaluating two control techniques to mitigate these issues: **Proportional-Integral (PI) controller with hysteresis current control**, and **Fuzzy Logic Controller (FLC) with hysteresis**. Both methods are implemented in a single-phase Zeta converter. Simulation results highlight that the fuzzy logic-based controller delivers better performance than the PI controller, demonstrating improved power quality, reduced harmonics, and more efficient voltage regulation.

Keywords - Single-Phase Zeta Converter, Power Factor Improvement, Total Harmonic Distortion (THD), Proportional-Integral (PI) Controller, Hysteresis Current Control, Fuzzy Logic Control.

INTRODUCTION

With the continuous advancements in power electronic systems, particularly those focusing on energy efficiency and high performance, the quality of power has emerged as a crucial concern across industries, households, and renewable energy applications. Power electronic converters like single-phase AC–DC rectifiers are extensively used in LED drivers, battery chargers, medical devices, and motor drives [3], [20], [31]. However, conventional AC–DC conversion methods, such as those using diode bridges with bulk capacitors, present several challenges, including low power factor, high peak input currents, harmonic distortion, and electromagnetic interference (EMI) [1], [9], [24], [25]. These issues significantly degrade the overall system efficiency and hinder grid compliance.

To address these challenges, topologies such as Zeta converters have garnered attention due to their ability to maintain continuous input current, provide buck–boost voltage regulation, and operate in both isolated and non-isolated configurations [7], [9], [13], [21], [29]. The Zeta converter's capacity to operate in Continuous Conduction Mode (CCM) makes it an ideal choice for power factor correction (PFC) and minimizing total harmonic distortion (THD) in AC–DC applications [1], [23], [27], [33]. Additionally, the Zeta converter demonstrates better electromagnetic compatibility compared to traditional boost converters.

The selection of control strategies is critical in optimizing converter performance. Conventional methods like Proportional–Integral (PI) and PI combined with Hysteresis Current Control (HCC) are commonly employed due to their simplicity and low computational demands; however, they face limitations under rapidly changing and nonlinear conditions [6], [10], [25]. HCC-based current shaping

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delivers excellent dynamic response but may cause fluctuating switching frequencies, complicating filter design and raising EMI concerns [17], [34]. Similarly, peak current mode control struggles with instability at lower duty ratios and is highly sensitive to noise interference.

In response, advanced control strategies like Fuzzy Logic Controllers (FLCs) and Artificial Neural Networks (ANNs) have gained prominence in power electronics [2], [14], [16], [23]. These intelligent controllers can handle parameter uncertainties, load variations, and nonlinear dynamics more effectively. Research has shown that FLCs improve dynamic performance, reduce THD, and enhance voltage regulation compared to traditional PI controllers [5], [11], [12], [15], [26]. Hybrid approaches such as fuzzy-HCC and ANN-fuzzy integration are increasingly used in Zeta, SEPIC, and Luo converter architectures [4], [19], [32].

The digital implementation of these control strategies using FPGA and DSP platforms has shown promising real-time performance in improving power quality [8], [28], [30]. Applications such as grid-connected renewable systems, LED lighting, and electric vehicle chargers highlight the necessity for robust control systems under fluctuating conditions [3], [20], [31], [33]. Comparative studies confirm that fuzzy-based control methods outperform traditional PI controllers in dynamic and real-time conditions [13], [23].

This paper proposes a fuzzy logic-based control strategy integrated with hysteresis current control for a single-phase AC–DC Zeta converter. Simulation and performance evaluation are conducted using MATLAB/Simulink, comparing the fuzzy logic-controlled converter with a PI–HCC-controlled counterpart to assess performance in terms of THD, power factor correction, and output voltage stability.

MODESOFOPERATION

The Zeta converter is a single-stage power converter that comprises a single switch, an output capacitor, a coupled inductor, a flying capacitor, and a diode. The circuit configuration of an isolated Zeta converter is illustrated in Fig. 1.

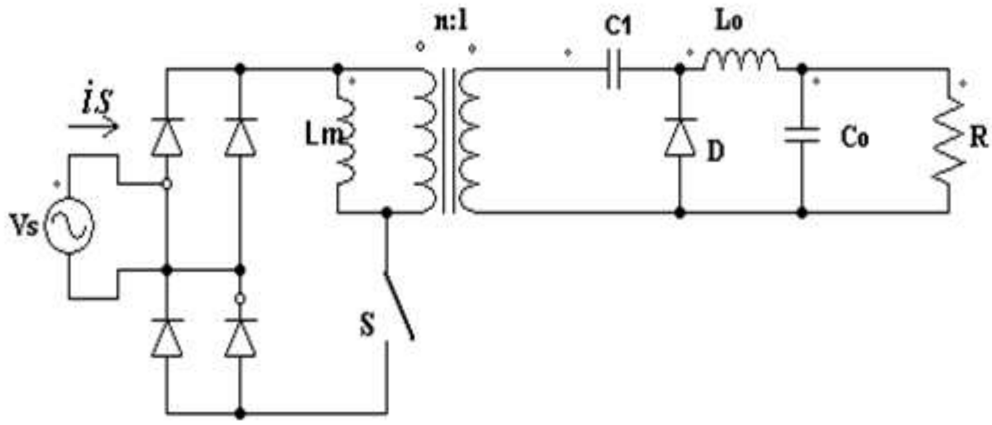

Fig.1. Schematic of an isolated Zeta converter

i. Mode1operation

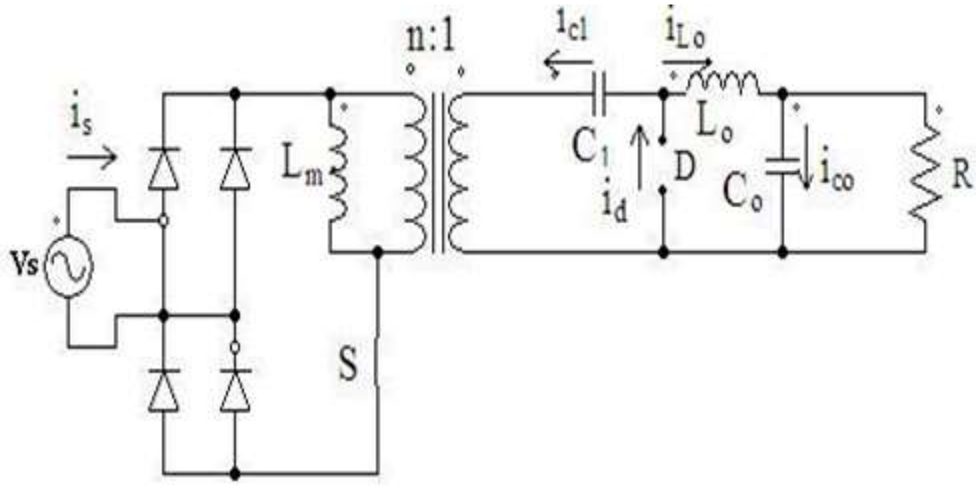

Fig.2Mode 1

Fig.2 shows illustrates Mode 1 operation of the isolated Zeta converter, corresponding to the interval when the switch **S** is turned ON. During this period, the current through both the magnetizing inductance and the output inductor increases linearly, driven by the applied input voltage across them. The expression for the magnetizing inductor current is given by,

$$i_m = i + \frac{V_{1r}}{L_m} t \quad (1)$$

Outputinductorcurrent during this mode is,

$$i_{L_o'} = -i + \frac{V_{1r}}{L_o'} t \quad (2)$$

During this mode, the flying capacitor discharges its stored energy to the load via the output inductor L_o. Since the diode remains reverse-biased, it does not conduct. Consequently, the currents through both the magnetizing inductor L_m and the output inductor L_o increase progressively.

ii.Mode 2operation

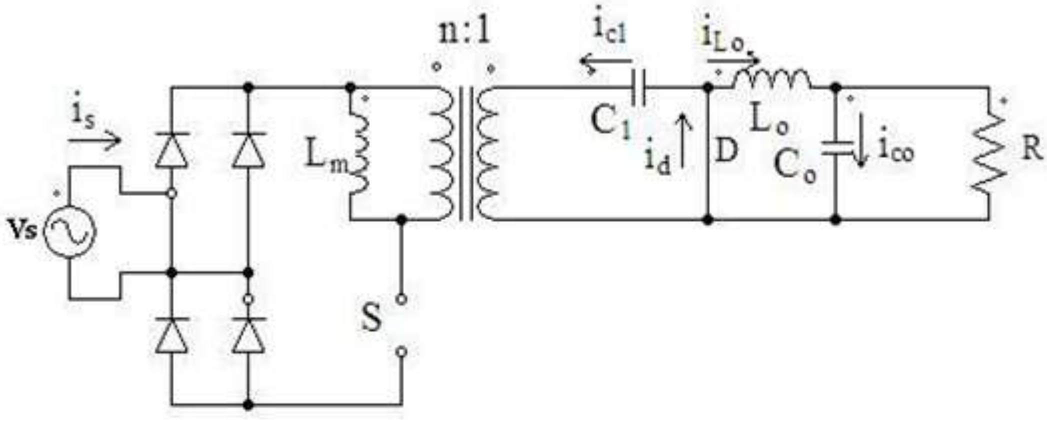

Fig. 3 Mode 2

Fig.3illustrates Mode 2 operation of the isolated Zeta converter, corresponding to the interval when the switch is turned OFF. In this mode, the diode D becomes forward-biased due to the reversal of polarity across the magnetizing inductor L_m. As a result, the diode conducts, and the currents through both L_m and L_o begin to decrease. The energy stored in L_m is now transferred to the flying capacitor C_1, while the load continues to receive current through the output inductor. This mode facilitates energy transfer and voltage modulation using the current-mode control technique. The magnetizing inductor current during this mode is given by,

$$= \frac{V_o'}{L_m}t + \frac{V_{1r}}{L_m}dT_s + i \quad (3)$$

Outputinductorcurrent during this mode is,

$$i_{L_o'} = \frac{V_o'}{L_o'}t + \frac{V_{1r}}{L_o'}dT_s - i \quad (4)$$

Fig.4illustrates the voltage and current waveforms across the magnetizing inductor L_m in a single-phase AC–DC isolated Zeta converter over one switching cycle.

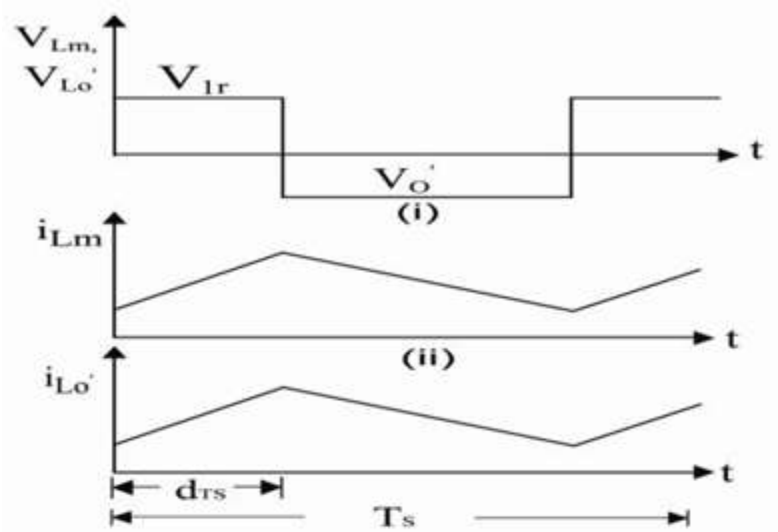

Fig.4Key waveforms observed in the operation of a Zeta converter

DESIGNSPCIFICATIONS

The voltage gain of the converter, denoted by (M)isgivenby,

$$M = \frac{V_o}{V_m} = \frac{nd_1}{(1-d_1)} \quad (5)$$

where,

V_o- Outputvoltage

V_m- thePeak input voltage

n- theTurnsratio

The output inductance L_o is determined using the following expression

$$L_o \geq \frac{(1-d_1)R}{2f_s} \quad (6)$$

MagnetizingInductanceis determined using the following expression

$$L_m \geq \frac{(1-d_1)^2 R}{2n^2 f_s} \quad (7)$$

ThevalueofflyingcapacitorC1 is determined using the following expression

$$C_1 \geq \frac{V_o d}{f_s R \Delta V_{c1}} \quad (8)$$

Where,

D_1 is theDutyratio

R is theLoadresistance

f_s istheSwitchingfrequency

ΔV_c is theVoltageripplеacrosstheflyingcapacitor

Output capacitorvalueiscalculatedusing,

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$$C_0 \geq \frac{V_O(1-d_1)}{8f_S 2L_O V_O} \quad (9)$$

Thedutyratio forthegivenconverterisobtainedby,

$$d_1 = \frac{M}{n+M} \quad (10)$$

Where,

MistheVoltagegain

nis theTurnsratio

Table1 Design criteria of the proposed Zeta converter

PARAMETERS	RATINGS
Inputvoltage V_{in}	12VRMS
Switchingfrequencyf_S	8 kHz
OutputvoltageV_O	48V
Outputpower P_O	23W
MagnetizinginductorL_m	422µH
OutputinductorL_O	3mH
Flyingcapacitor C_1	10mF
OutputcapacitorC_O	10mF
Dutyratio d_1	0.74
LoadresistanceR	100ohm

CONTROLLERS

i ***PIController***

Proportional–Integral (PI) control is the most commonly used closed-loop control method. The PI controller effectively eliminates steady-state error and forced oscillations, which are typically observed in on–off control systems. It acts as a voltage regulator and is utilized to compensate for variations in the DC-link voltage while reducing voltage ripple across the capacitors.

ii ***HysteresisController***

Hysteresis control is primarily used in AC/DC converters to ensure that the AC line current follows a specified reference. In Zeta converters, the hysteresis controller regulates the inductor current. This control method turns the switch ON when the inductor current falls below the lower reference and turns it OFF when the current exceeds the upper reference, resulting in variable frequency switching. A system based on this control approach is illustrated in **Fig. 4**.

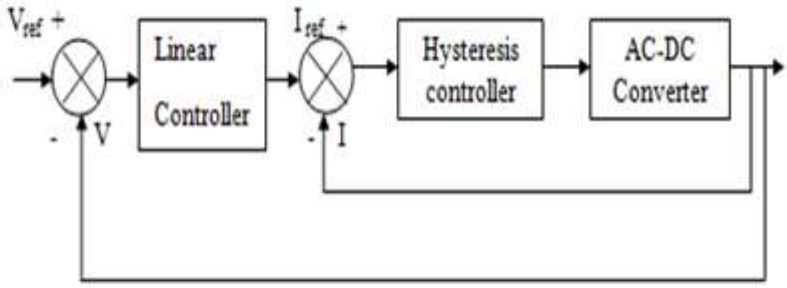

Fig.4Block diagramofproposedconverterwithhysteresiscontroller

iii ***FuzzyLogicControllers***

Fuzzy logic idea is similar to the human being feeling and inference process. The output of a fuzzy logic controller(FLC)isderivedfromfuzzificationofbothinputs andoutputs usingthe associatedmembershipfunctions.The outputofafuzzylogiccontrollerisbasedonitsmemberships todifferentmembershipfunctions,whichcanbeconsidered asarangeof inputs.InsinglephaseAC-DCZetaconverterthe fuzzy logiccontrollerisusedasvoltagecontrolloop.Here mamdani method is used and triangular membership is selected.Thelargerthenumberoffuzzylevels,thehigheristheinput resolution.Heresevenlevelsand49ruleshavebeen used.

SIMULATIONRESULTSANDANALYSIS

i *Openloopcontrol*

In this paper, simulation of the Zeta converter has been performed with a resistive load. Fig. 5 shows the simulated circuit diagram of the open-loop control of a single-phase AC–DC Zeta converter with a resistive load. The Zeta converter is fed by a 1φ supply with a line voltage and frequency of 12 V and 50 Hz, respectively. The rectified voltage is fed to the Zeta converter. A pulse generator is used to apply the gating pulses.

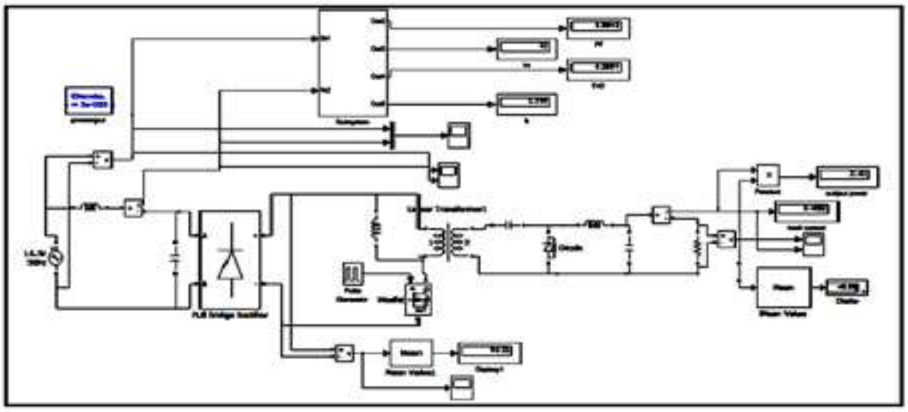

Fig.5 Openloopsimulinkmodelofsinglephase AC-DCZeta converter

Table 2 Analysis of AC to DC Zeta converter performance under varying load resistance

OutputPower (W)	Outputvoltage (V)	SourceCurrent THD(%)	Power factor	Efficiency(%)
100	48.11	26.12	0.987	68.22
80	51.22	36.04	0.981	67.59
60	55.69	38.51	0.975	67.25
40	62.15	40.73	0.964	66.81

Table 2 shows the open-loop control performance of the AC to DC Zeta converter with variation in load resistance. It is observed that the output voltage is not regulated under these conditions

ii *PIvoltage controllerandHysteresis currentcontroller*

Fig. 6 shows the simulated circuit diagram of the closed-loop control analysis of the AC–DC Zeta converter using a PI controller with hysteresis current control (HCC). In this configuration, the output voltage is compared with a reference voltage (V_{ref}), and the resulting error is fed to the PI controller.

In the HCC scheme, the rectified output voltage is multiplied by the PI controller output to generate the current reference. This reference is then compared with the inductor input current, and the resulting signal is processed through a relay. The relay output is used to generate the gating pulses for the switch.

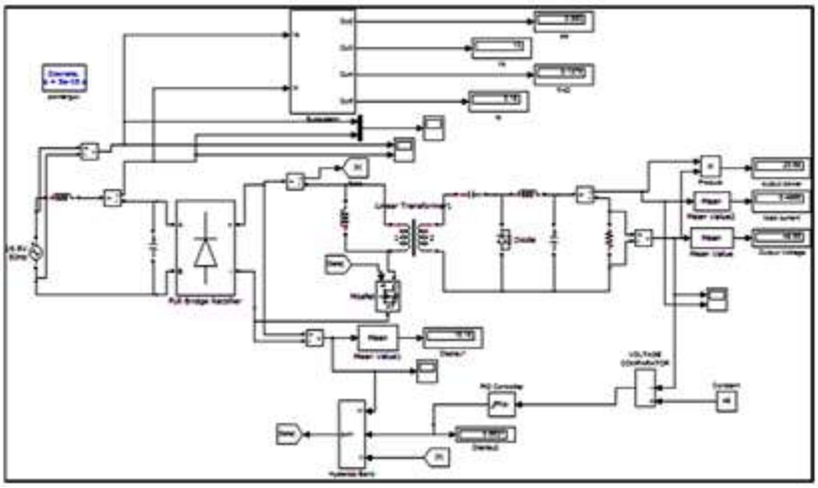

Fig.6 Simulink model of the AC to DC Zeta converter using a PI voltage controller and hysteresis current controller

Table 3. Performance analysis of the AC to DC Zeta converter with PI voltage controller and hysteresis current controller under varying load resistance

OutputPower (W)	Outputvoltage (V)	SourceCurrent THD(%)	Powerfactor	Efficiency(%)
100	48	9.85	0.990	78.21
80	48	12.78	0.983	74.44
60	48	15.56	0.981	74.10
40	48	18.97	0.976	72.69

Table 3 shows the performance analysis of the AC to DC Zeta converter with a PI voltage controller and hysteresis current controller under varying load resistance. It is observed that the output voltage is regulated to 48 V, and the source-side harmonics are significantly reduced.

iii *Fuzzy Logic-Based Voltage Regulation Using Hysteresis Current Controller*

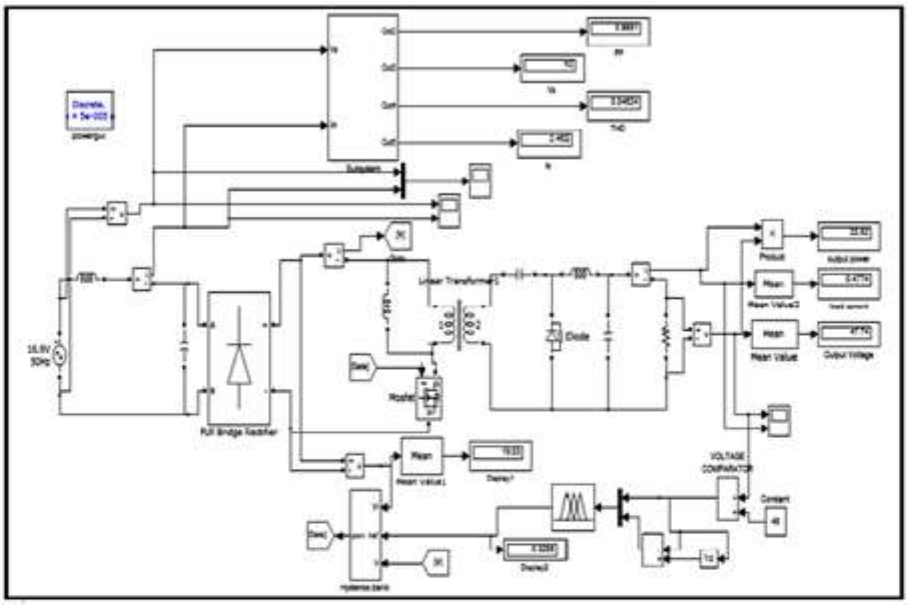

Fig.7Simulink model of an AC–DC Zeta converter employing fuzzy voltage control along with hysteresis current controller.

Fig. 7 illustrates the simulated circuit model for generating control signals using a fuzzy voltage controller along with a hysteresis current controller. Fig. 8 displays the input voltage and input current waveforms. From these waveforms, it is evident that the input power factor is close to unity, and the input current distortion is significantly reduced when compared to the system utilizing a PI voltage controller with hysteresis current control.

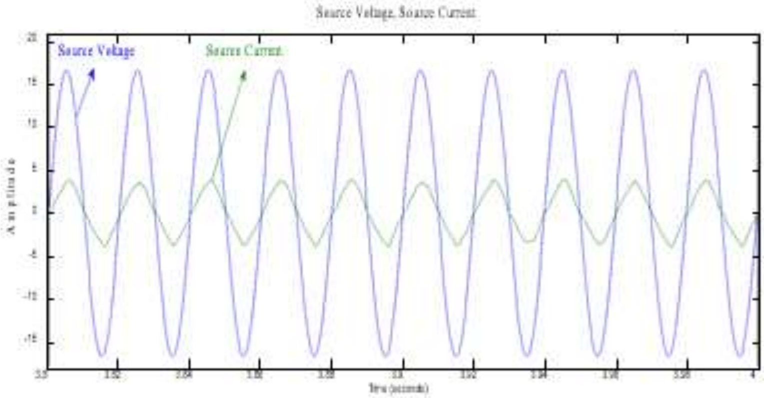

Fig.8Input Side Voltage and Current Waveforms

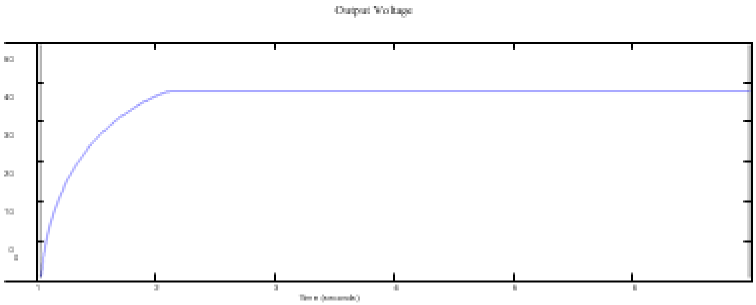

Fig.9Output Voltage Response of the Single-Phase AC–DC Zeta Converter

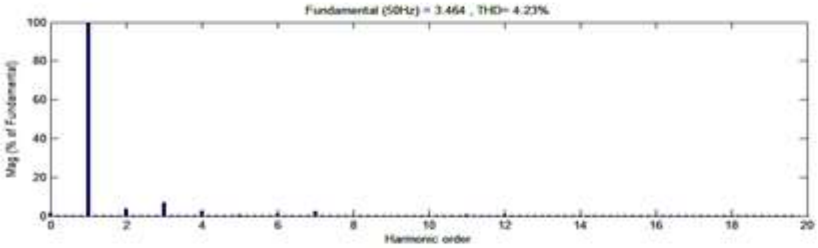

Fig.10FFT spectrum

Fig. 9 shows the output voltage waveform of the AC to DC Zeta converter using a fuzzy voltage controller combined with a hysteresis current controller. It is observed that the output voltage is effectively regulated to 48 V. The corresponding FFT analysis is presented in Fig. 10.

Table 4 presents the performance analysis of the AC to DC Zeta converter with fuzzy voltage control and hysteresis current control under varying load resistance

OutputPower (W)	Outputvoltage (V)	SourceCurrentTHD(%)	Power	Efficienc
100	48	4.23	0.999	80.51
80	48	5.54	0.997	78.33
60	48	7.10	0.986	77.27
40	48	7.82	0.983	77.01

Table 4 shows the performance of the converter under varying load resistance conditions using a fuzzy voltage controller and hysteresis current controller. As the load resistance is varied, the corresponding source current THD and power factor are observed. It is noted that with an increase in load resistance, the output voltage remains well regulated.

EVALUATION OF SIMULATION OUTCOMES

The performance parameters such as Total Harmonic Distortion (THD), power factor, efficiency, and output voltage regulation of the single-phase AC to DC Zeta converter are compared for different control techniques. The comparative results are presented in Table 5.

Table5Comparativeanalysis

Controller	Output voltage (V)	Sourceside THD (%)	Power factor	η (%)
Openloop	48.11	26.12	0.987	68.22
PI–Hys	48	9.85	0.990	78.21
Fuzzy–Hys	48	4.23	0.999	80.51

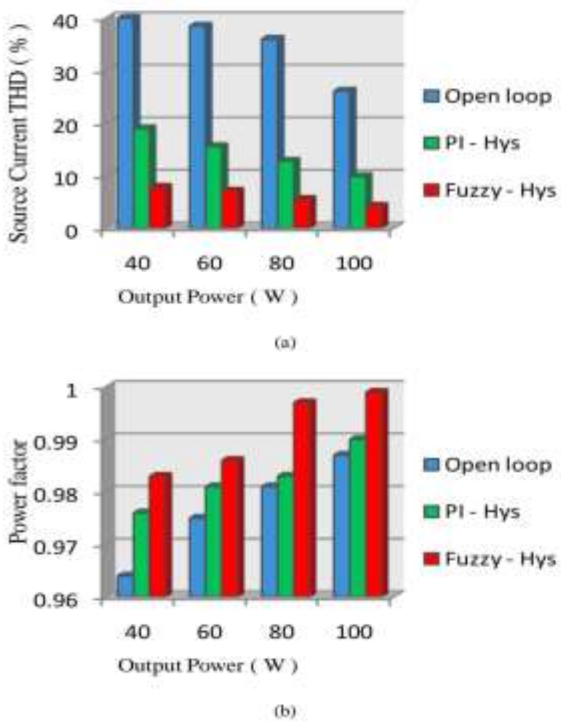

Fig. 11 (a), (b) Performance analysis

Fig. 11 (a), (b) shows the performance analysis of the single-phase AC–DC isolated Zeta converter using various control strategies.

CONCLUSION

The closed-loop performance of a single-phase AC to DC Zeta converter has been analyzed using two different control strategies: PI voltage controller with hysteresis current controller, and fuzzy voltage controller with hysteresis current controller. These simulations were conducted using MATLAB. The fuzzy voltage controller with hysteresis current control is proposed to achieve improved power quality, featuring a high-power factor, low current distortion, and stable output voltage. The simulation results indicate a significant reduction in source current THD to 4.23% and a power factor of 0.999, demonstrating minimal harmonic distortion. Among the two control methods, the fuzzy voltage controller with hysteresis current controller is found to be the superior technique for enhancing the power quality of the converter.

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