Hybrid FLC/BFO Controller for Output Voltage Regulation of Zeta Converter

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Abstract— Renewable energy sources are usually connected to the power grid via power converters. Zeta converters are very important for microgrid and smart grid applications. The objective of this paper is to design a Mamdani fuzzy logic controller (FLC) and a hybrid fuzzy logic controller with the bacterial foraging optimization algorithm (FLC/BFO) to improve and regulate the output voltage response against disturbances like the change in the voltage source or the load for the Zeta converter operating in continuous conduction mode (CCM). Analysis and comparison among simulations of the open loop, closed loop fuzzy logic controller, and hybrid FLC/BFO controller results were performed for different output voltages and for different working conditions such as the change in the voltage source or the load. The results show that there is a significant improvement in the results for the proposed FLC/BFO controller. The designs and simulations were performed in MATLAB/SIMULINK environments. The results were compared with other results which used the particle swarm optimization (PSO) algorithm.

Index Terms— Bacterial Foraging Optimization Algorithm, Continuous Conduction Mode, Fuzzy Logic Controller, Renewable Energy Sources, Zeta Converter.

I INTRODUCTION

Power systems produce electricity depending on load demands. Over the years, load demands increased in devloped countries. Energy sources have limitations on relability of the supply, and cause environmental pollution, global warming, and the risk of occurrence of nuclear accidents; thus, a need for renewable energy sources was born [1], such sources include wind, solar, hydro, and geothermal [2]. Renewable energy sources are usually connected to power grids via power converters. The choice of the appropriate topology for inverters depends on many factors such as the type of the renewable energy source and the total amount of power that will be handled [3].

DC to DC Zeta converters are one type of converters that are used to interface renewable energy sources to the grid. Moreover, Zeta converters are used in many applications like supplying suitable DC voltage to modern portable electronic equipment which are not directly connected to the AC mains, power quality improvements, power factor correction, and industrial applications. In this paper, we will use a Zeta converter for converting and supplying suitable DC voltage from a DC voltage source to a load.

In June 2010, Vuthchhay and Bunlaksananusorn used a linearized model Zeta converter in the CCM mode to regulate the output voltage against disturbances [4]. In order for the output voltage to meet a desired value, a PWM feedback controller was used, then a PI controller was added to improve the system response. In 2011, Moaveni, et.al. presened a model reference adaptive controller (MRAC) with back-propagation neural networks (NN) to control the output voltage of the Zeta converter operating in CCM [5]. In 2012, Izadian, et.al. implemented a model reference adaptive controller (MRAC) to the Zeta converter operating in CCM mode for output voltage tracking [6].

In 2013, Sarkawi, et.al. studied the Zeta converter operating in the CCM mode to regulate the output voltage using a full-state feedback controller [7]. They presented the system model by the SSA technique. The small signal linear model considered two inputs to the system: the input voltage and the load current. The feedback gain matrix K was found by two methods: the pole placement method and the linear quadratic regulator (LQR). They found that LQR gave them better results than the pole placement method, because LQR found the optimal control effort. But their system model was complicated.

In June 2014, Ahmad and Sultan studied the Zeta converter operating in CCM mode to improve its output voltage, and to control the output voltage under different working conditions or disturbances such as changes in the load resistance or input voltage [8]. A fuzzy logic controller (FLC) and a FLC with particle swarm optimization which is known as a hybrid FLC/PSO controller were presented to achieve the control goal. They compared the results of the open loop system with FLC and FLC/PSO which concluded that FLC/PSO produced the best results. Sarkawi, et.al. work's is one of the few reported works in the literature to present a hybrid FLC/PSO controller, which reduced the system modeling of Zeta converter for controlling the output voltage. But the output response had small ripples.

This paper presents a design of a fuzzy logic controller (FLC) to reduce the control complexity of the Zeta converter system in CCM mode to improve its performance under different working conditions such as the load and the voltage source disturbances. The designs and simulations were performed in MATLAB/SIMULINK environments. The main contribution is to use a new optimization algorithm which is the Bacterial Foraging Optimization Algorithm (BFOA) to improve the FLC performance by optimizing its scaling gains, which results in designing a hybrid FLC/BFO controller [9]. The effectiveness of the BFO algorithm will be proved via the improvement of the FLC performance for different working conditions.

This paper is organized as follows: Section 2 presents Zeta converter and its modeling using the SSA technique. Section 3 presents the fuzzy logic control design. Section 4 presents the Bacterial Foraging Optimization Algorithm (BFOA) as an optimization method that will be used to get the best performance for the FLC. Section 5 presents the hybrid FLC/BFO controller design. Section 6 presents the results and discussion. Section 7 concludes this paper and presents the future work. Section 8 presents the references.

II ZETA CONVERTER AND ITS MODELING

Zeta converter is a 4^{th} order nonlinear DC-DC converter [10], as shown in Figure 1, has two inductors each with a DC Resistance (DCR), two capacitors each with an Equivalent Series Resistance (ESR), and a diode. The Zeta converter can operate in step up or step down modes to supply a load.

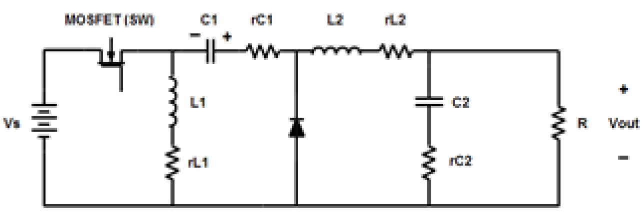
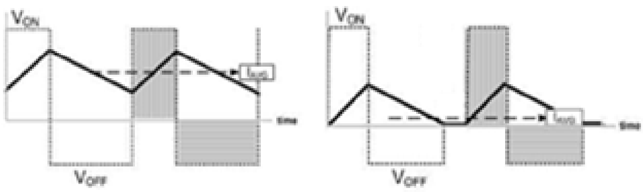


Figure 1 Zeta converter circuit

The input to the Zeta converter is a DC voltage. The Zeta converter circuit has an operating switch (MOSFET). Zeta converters may operate in one of two operating modes, the first mode is the Continuous Current Mode (CCM), and the second mode is the Discontinuous Current Mode (DCM).

Within one switching period T, CCM mode offers two circuit states while DCM mode offers three circuit states. This paper focuses on CCM mode. Figure 2 illustrates the difference between CCM and DCM modes in ON and OFF states [11].



(a) CCM mode (b) DCM mode

Figure 2 Inductors currents waveforms in CCM and DCM modes

The modeling of the converter is represented as a state space model. As explained in the next section, the overall model is obtained by the state space averaging technique (SSA) from two state space models by calculating the weighted average of two sets of equations using the nominal values of the time spent in each circuit state as the weights.

A Description of Each Circuit State

When the MOSFET switch is ON, the diode is reverse biased, thus - open circuited as shown in Figure 3 below. In this state, the inductors L_1 and L_2 are in the charging state, and the inductors currents are increasing linearly.

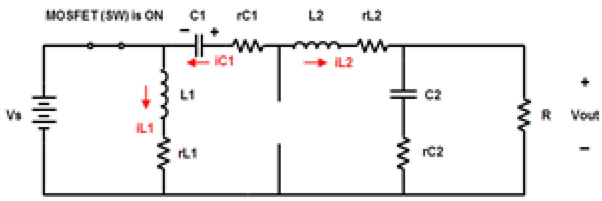


Figure 3 The equivalent Zeta converter circuit when the switch is ON

The second state is when the MOSFET switch is OFF, the diode is forward biased, thus - short circuited as shown in Figure 4 below. In this state, the inductors are in the discharging state, and the energies in L_1 and L_2 are discharged to capacitors C_1 and C_2 which are the output parts respectively, and the inductors currents are decreasing linearly.

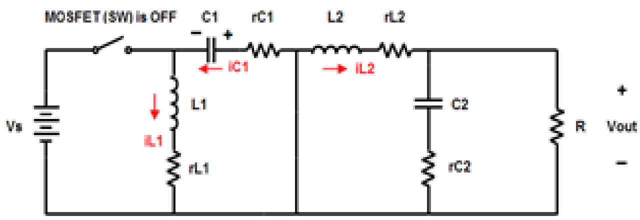


Figure 4 The equivalent Zeta converter circuit when the switch is OFF

To insure that inductors currents are increasing and decreasing linearly, the following equations must be satisfied [4]:

$$\begin{cases} L_1 > \dfrac{(1-D)^2 R}{2Df}\left(1+\dfrac{r_{L2}}{R}+\dfrac{r_{C1}}{R}\dfrac{D}{1-D}\right) \\ L_2 > \dfrac{(1-D)R}{2f}\left(1+\dfrac{r_{L2}}{R}\right) \end{cases} \quad (0)$$

Where f is the switching frequency and D is the duty cycle of the switch.

B State Space Modeling of Each Circuit State

When the MOSFET switch is ON as shown in Figure 3,the state space model is as follows:

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r_{L1}}{L_1} & 0 & 0 & 0 \\ 0 & \frac{-1}{L_2}\left(r_{L2}+r_{C1}+\frac{r_{C2}R}{r_{C2}+R}\right) & \frac{1}{L_2} & \frac{-R}{L_2(r_{C2}+R)} \\ 0 & \frac{-1}{C_1} & 0 & 0 \\ 0 & \frac{R}{C_2(r_{C2}+R)} & 0 & \frac{-1}{C_2(r_{C2}+R)} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \\ 0 \end{bmatrix} v_s$$

$$v_o = \begin{bmatrix} 0 & \frac{r_{C2}R}{r_{C2}+R} & 0 & \frac{R}{r_{C2}+R} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix}$$

When the MOSFET switch is OFF as shown in Figure 4, the state space model is as follows:

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{L_1}(r_{C1}+r_{L1}) & 0 & \frac{-1}{L_1} & 0 \\ 0 & \frac{-1}{L_2}\left(r_{L2}+\frac{r_{C2}R}{r_{C2}+R}\right) & 0 & \frac{-R}{L_2(r_{C2}+R)} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{R}{C_2(r_{C2}+R)} & 0 & \frac{-1}{C_2(r_{C2}+R)} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix}$$

$$v_o = \begin{bmatrix} 0 & \frac{r_{C2}R}{r_{C2}+R} & 0 & \frac{R}{r_{C2}+R} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix}$$

C State Space Averaging Technique (SSA)

During the first state, the MOSFET switch is ON for an interval DT, while during the second state the MOSFET switch is OFF for an interval (1-D)T. The averaged (overall) state space model for the Zeta converter is obtained as follows [7]:

$$\begin{aligned} A_{av} &= A_1 D + A_2(1-D) \\ B_{av} &= B_1 D + B_2(1-D) \\ C_{av} &= C_1 D + C_2(1-D) \end{aligned} \quad (2)$$

In this paper, we assume ideal Zeta converter, where all DC Resistances and Equivalent Series Resistances have a value of zero; thus, the state space model becomes as follows:

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{D-1}{L_1} & 0 \\ 0 & 0 & \frac{D}{L_2} & \frac{-1}{L_2} \\ \frac{1-D}{C_1} & \frac{-D}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & \frac{-1}{RC_2} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{D}{L_1} \\ \frac{D}{L_2} \\ 0 \\ 0 \end{bmatrix} v_S \quad (3)$$

$$v_O = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix}$$

The relation between the input and the output voltages in the ideal Zeta converter is characterized by the duty ratio as follows [4]:

$$v_O = v_S\left(\frac{D}{1-D}\right) \quad (4)$$

For CCM mode, the critical values for the inductance and capacitance in the ideal Zeta converter are as follows [4]:

$$\begin{cases} L_1 \geq \dfrac{(1-D)^2 R}{2Df} \\ L_2 \geq \dfrac{(1-D)R}{2f} \\ C_1 \geq \dfrac{D}{8f(1-D)R} \\ C_2 \geq \dfrac{1}{8fR} \end{cases} \tag{5}$$

The produced ripples in the inductors currents and in the capacitors voltages in the ideal Zeta converter are given in terms of v_s and f, the switching frequency, as follows [8]:

$$\begin{cases} \Delta i_{L1} = \dfrac{Dv_s}{fL_1} \\ \Delta i_{L2} = \dfrac{Dv_s}{fL_2} \\ \Delta v_{C1} = \dfrac{Dv_s}{8f^2 C_1 L_1} \\ \Delta v_{C2} = \dfrac{Dv_s}{8f^2 C_2 L_2} \end{cases} \tag{6}$$

III FUZZY LOGIC CONTROLLER

In this paper, three linguistic variables are used which are two input variables to the fuzzy logic controller; (the error, and the change of the error), and one output variable; that is the control signal to the Zeta converter system after being defuzzified. Each input variable has 5 triangular membership functions; thus, forming 5*5 or 25 rules. The Mamdani inference system is used, and the centroid method is used as the defuzzification method.

The membership functions and their ranges for the three linguistic variables are as shown in Figures 5-7:

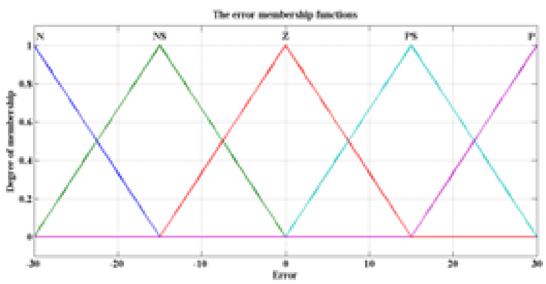


Figure 5 The error MF

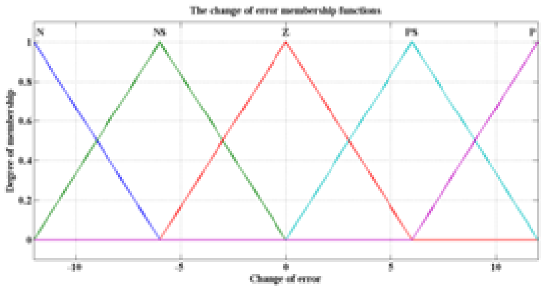


Figure 6 The change of the error MF

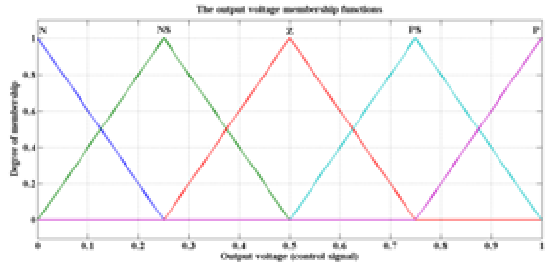


Figure 7 The output voltage MF

TABLE 1
The rule base of the FLC

E / ΔE	N	NS	Z	PS	P
N	N	N	N	NS	Z
NS	N	N	NS	Z	PS
Z	N	NS	Z	PS	P
PS	NS	Z	PS	P	P
P	Z	PS	P	P	P

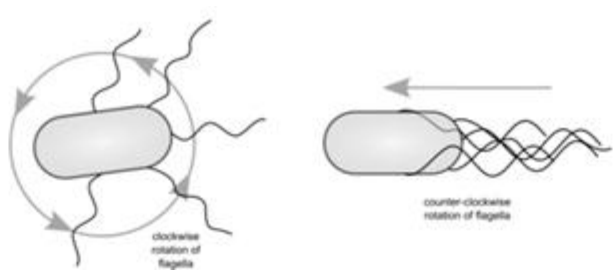
The Fuzzy Associative Memory (FAM) or the table of rules is shown in Table 1 [8]:

The membership functions shown in Figures 5-7 need to be tuned in addition to the FLC scaling gains for the inputs which represent a PD controller, and for the output in order to get the desired output performance. Thus, the control is achieved by a FLC with PD controllers. The tuning was performed manually as it will be explained in section 5.

IV BACTERIAL FORAGING OPTIMIZATION ALGORITHM (BFOA)

Bacterial foraging optimization algorithm (BFOA) proposed by Passino [12] is a simulation of the social foraging behavior of Escherichia coli bacteria present in human intestine.

Generally, this type of bacteria move for a longer distance in a friendly environment. The chemotaxis of bacteria could be a continuous swim, a swim followed by a tumble, a tumble followed by a tumble, a tumble followed by a swim, or a combination of them. [13]. Figure 8 shows the swim and tumble modes for a bacterium.



(a) Tumble mode (b) Swim mode

Figure 8 Modes of an E.coli bacterium

A Processes of BFOA

If $J(\theta)$ is the problem to be optimized, where θ is a p dimensional vector, the four processes of the BFOA are as follows:

1. Chemotaxis

The chemotactic step is considered to be a tumble followed by a tumble, or a tumble followed by a swim. Let $P(j,k,l)=\{\theta^i(j,k,l)\,|\,i=1,2,...,S\}$ represent the position of each bacterium of the population at the j-th chemotactic step, k-th reproduction step, and l-th elimination dispersal event, or simply θ^i. The position of the bacterium in the next chemotactic step after a tumble can be represented as follows:

$$\theta^i(j+1,k,l)=\theta^i(j,k,l)+C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \qquad (7)$$

Where Δ is a vector in the random direction whose elements lie in [-1,1]. If the fitness values of the bacterium improved after the tumble, it will continue swimming until the fitness value degrades, then it will tumble.

2. Swarming

Swarming means that the bacteria send signals to each other to congregate into high bacterial density groups and move to reach the desired location. Let $j(i,j,k,l)$ represent the cost or fitness at the location of the i-th bacterium $\theta^i(j,k,l)$. Swarming can be represented as follows:

$$J_{CC}(\theta,P(j,k,l))=\sum_{i=1}^{S}J_{CC}(\theta,\theta^i(j,k,l))$$
$$=\sum_{i=1}^{S}[-d_{attractant}\exp(-w_{attractant}\sum_{m=1}^{p}(\theta_m-\theta^i{}_m)^2)]+ \qquad (8)$$
$$\sum_{i=1}^{S}[h_{repellant}\exp(-w_{repellant}\sum_{m=1}^{p}((\theta_m-\theta^i{}_m)^2)]$$

Where $J_{CC}(\theta,P(j,k,l))$ is the fitness function value to be added to the actual fitness function which is to be optimized to present a time varying fitness function, $\theta=[\theta_1,\theta_2,...,\theta_p]^T$ is a point in the p dimensional search domain, and $d_{attractant}$, $w_{attractant}$, $h_{repellant}$, and $w_{repellant}$ are different coefficients which should be chosen properly.

3. Reproduction

The reproduction means that the bacteria which have had sufficient nutrients will reproduce an exact replica of itself, and the least healthy bacteria will die. The number of the reproduced bacteria will equal the number of the dead ones, thus, the population size of the bacteria will be constant in the evolution process.

4. Elimination and Dispersal

Elimination and dispersal simulates the sudden environmental changes or attacks that may occur in the real bacteria, thus, a group of bacteria may be killed, and others may move to some other places. While simulation, this reduces the trapping in a local optimal point.

V Hybrid FLC/BFO Controller

In this paper, we will optimize the scaling gains for the normalized manually tuned membership functions by using the integral of the absolute value of the error or IAE as the fitness function.

The scaling gains for the inputs and the output of the FLC will be used as variables that will be optimized using BFOA. In this case, the controller is called hybrid FLC/BFO controller.

The BFO algorithm will produce trial solutions for the scaling gains, and it will determine if they minimize the error in the system response by using the integral of the absolute value of the error as a fitness function. Then, the best scaling gains will be selected for the best system response. Figure 9 illustrates the process of the hybrid FLC/BFO controller to control a system plant.

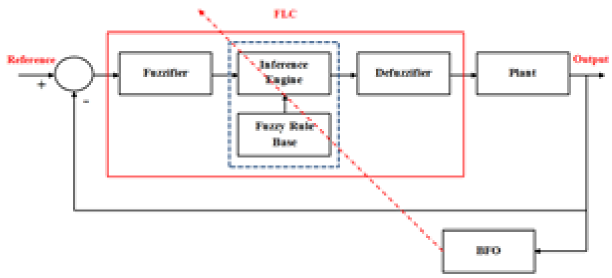


Figure 9 Hybrid FLC/BFO controller

VI Results And Disscussion

The simulation of the open loop Zeta converter system, the designing of a fuzzy logic controller (FLC) for the closed loop Zeta converter system, and the designing of a hybrid FLC/BFO for the closed loop Zeta converter system were performed for different output voltages 9, 12, and 15 V for the nominal values under different working conditions such as load disturbance, voltage source disturbance, or both. Comparisons were made between our results and the results of Ahmad, et.al [8] to demonstrate the effectiveness of our results and our methodology. The designs and simulations were performed under MATLAB/SIMULINK environment.

A The Normal Open Loop Zeta Converter System Analysis

The averaged state space model in equation (3) has six variables that must be defined in order to find the state space matrices which are L_1, L_2, C_1, C_2, R, and D. The critical values of L_1, L_2, C_1, and C_2 in CCM mode mainly depend on the switching frequency f, the Load R, and the duty ratio D. The inductors currents and the capacitors voltage ripples are also affected. The critical values or limits and the inductors currents and the capacitors voltage ripples are as shown in equations (5) [4] and (6) [8] respectively.

The duty ratio D can be obtained as follows:

$$D = \frac{V_O}{V_O + V_S} \tag{9}$$

TABLE 2
The duty ratio for different voltages

	The output voltage (V_O) V	The duty ratio (D)
V_S = 12 V	9	0.428
	12	0.5
	15	0.555

Selecting $V_S = 12$ V, then, for each V_O, there is a duty ratio D. Table 2 illustrates the duty ratio D for $V_O = 9,\ 12,$ and 15 V.

TABLE 3
Critical values parameters

Zeta converter parameters	V_S=12 V		
	V_O=9 V, D=0.428	V_O=12 V, D=0.5	V_O=15 V, D=0.555
L_1 (mH)	0.764	0.5	0.356
L_2 (mH)	0.572	0.5	0.445
C_1 (µF)	1.87	2.5	3.12
C_2 (µF)	2.5	2.5	2.5

Table 3 illustrates the critical values or limits for L_1, L_2, C_1, and C_2 under different D and different V_O when the switching frequency f = 5kHz and the load $R = 10\ \Omega$.

It is clear that we must choose values that satisfy all the critical limits in order to design a Zeta converter system that is valid for converting the input voltage to the output voltages 9, 12, and 15 V, in which we must choose $L_1 \geq 0.764$ mH, $L_2 \geq 0.572$ mH $C_1 \geq 3.12\ \mu$F, and $C_2 \geq 2.5\ \mu$F

TABLE 4
The Zeta converter parameters

Zeta converter system parameters	
F	5 kHz
R	10 Ω
L_1	5 mH
L_2	5 mH
C_1	90 μF
C_2	10 μF

Table 4 illustrates the values for the Zeta converter system parameters that are used in this paper.

The normal open loop responses with the reference voltages are shown in Figure 10. The normal open loop systems performances are illustrated in Table 5.

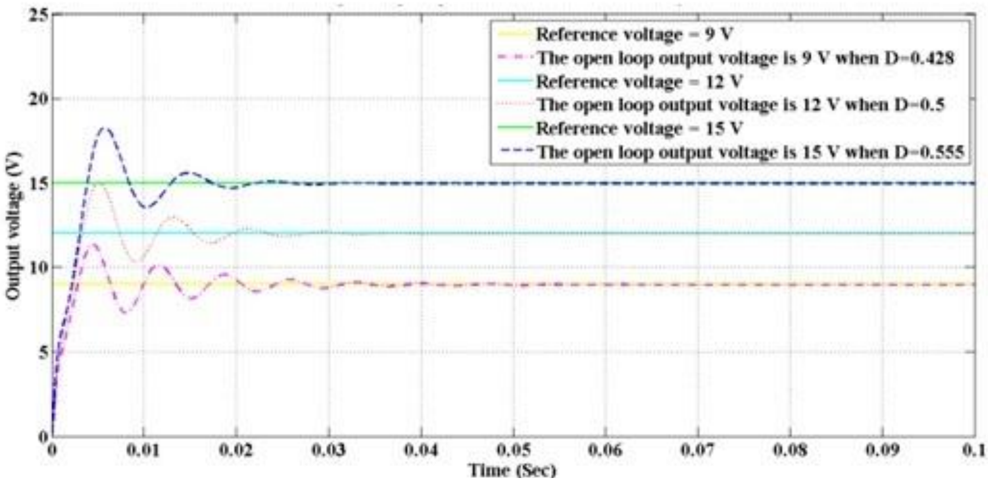


Figure 10 The normal open loop system responses

TABLE 5
The normal open loop Zeta converter systems performances

V_S (V)	D	V_O (V)	The normal open loop Zeta converter systems performances			
			OS (%)	t_s (ms)	e_{ss} (%)	V_O ripples (V)
12	**0.428**	**9**	26.5	28.9	0.23	0.513
	0.5	**12**	25.33	20.5	0	0.6
	0.555	**15**	22.15	14.7	0.22	0.66

B Fuzzy Logic Controller Analysis

The simulation of the three normal closed loop Zeta converter systems which are for tracking the output voltages $V_O = 9$, 12, and 15 V when $V_S = 12$ V compared with the three normal open loop Zeta converter systems for a simulation time $t = 0.1$ sec is shown in Figure 11.

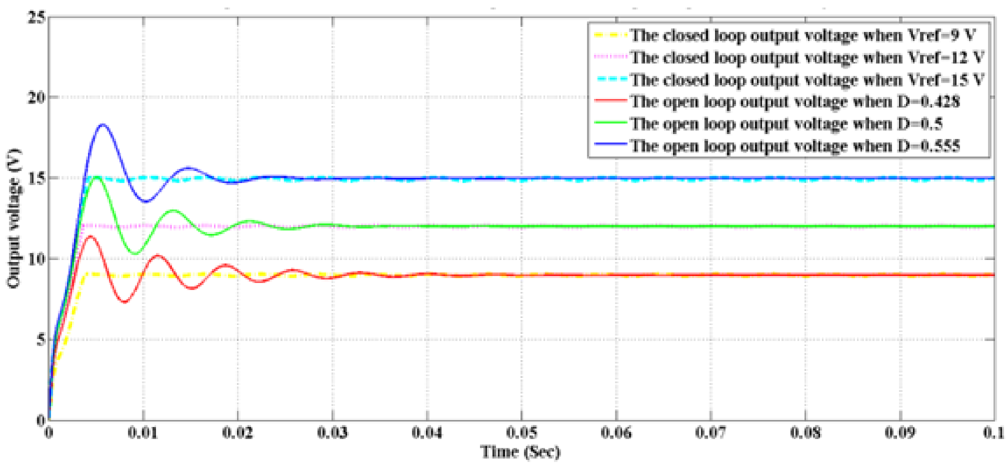


Figure 11 The response of the normal FLC closed loop and the normal open loop Zeta converter

The normal FLC closed loop systems performances are illustrated in Table 6.

TABLE 6
The normal FLC closed loop Zeta converter systems performance

V_S (V)	V_{Ref} (V)	The normal FLC closed loop Zeta converter systems performances			
		OS (%)	t_S (ms)	e_{SS} (%)	V_O ripples (V)
12	**9**	1.49	2.8	0.67	0.128
	12	0.74	3.6	0.71	0.128
	15	0.50	4.15	0.9	0.153

A comparison between Table 6 and Table 5 which is for the normal open loop systems performances is shown in Figure 12.

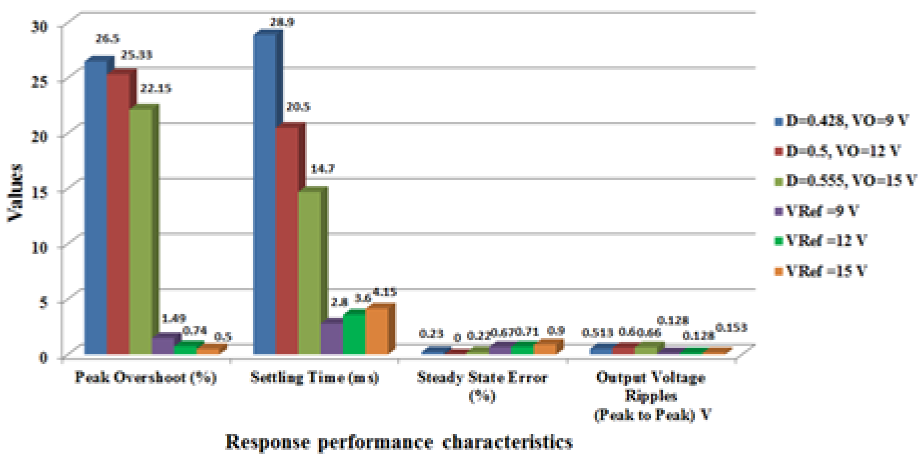


Figure 12 The normal FLC closed loop Vs. normal open loop systems

C The System Disturbance Analysis

The simulation of the open loop and the closed loop Zeta converter systems for the output voltages 9, 12, and 15 V with a simulation time $t = 0.15$ sec under fuzzy logic controller is performed here. Changes in the load current and the load voltage is followed efficiently when the load changes, voltage source changes, or both occur; thus, protecting the load from damage or malfunctioning.

C.1 System Analysis with the Load Disturbance

The load R is considered to change linearly sweeping the values $10-40-10\ \Omega$, in which it starts to change from $10\ \Omega$ at time $t = 0.05$ sec to reach $40\ \Omega$ at time $t = 0.1$ sec, then it will change from $40\ \Omega$ to reach $10\ \Omega$ at time $t = 0.15$ sec. Figure 13 shows the changes in the values of the gain 1/R. The response of the three closed loop

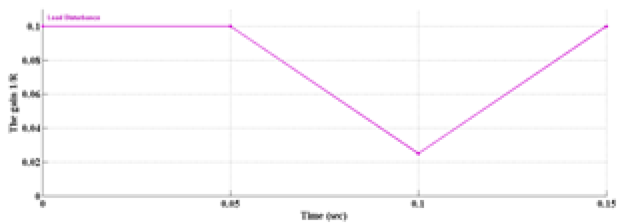


Figure 13 The load disturbance in the 1/R gain signal

Zeta converter systems compared with the three open loop systems with load disturbance is shown in Figure 14.

It is clearly shown that the open loop response is affected by the load change in which the variations in the open loop output voltage according to the load change increase as the converted output voltage increases, while in the FLC closed loop systems, these variations were minimized and are under control.

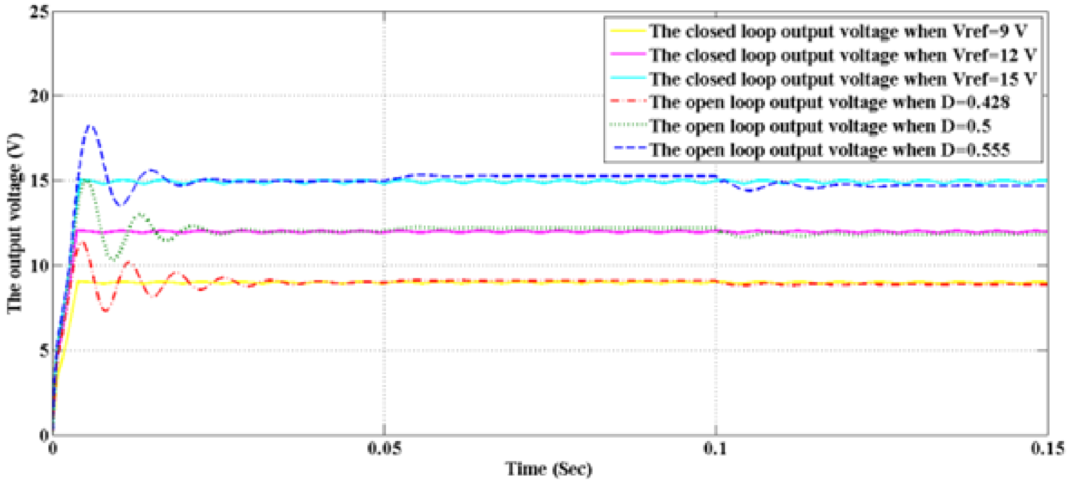


Figure 14 FLC closed loop and open loop systems response with load disturbance

C.2 The System Analysis with the Voltage Source Disturbance

The voltage source V_S is considered to change linearly sweeping the values $12-11-13-14-12$ V, in which it starts to change from 12 V at time $t = 0.05$ sec to reach 11 V at time $t = 0.055$ sec, then it will change from 11 V to reach 13 V at time $t = 0.1$ sec, then it will change from 13 V to reach 14 V at time $t = 0.125$ sec, then it will change from 14 V to reach 12 V at time $t = 0.15$ sec. Figure 15 shows the changes in the values of the voltage source.

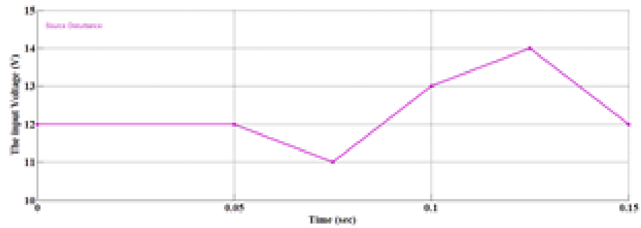


Figure 15 The voltage source disturbance signal

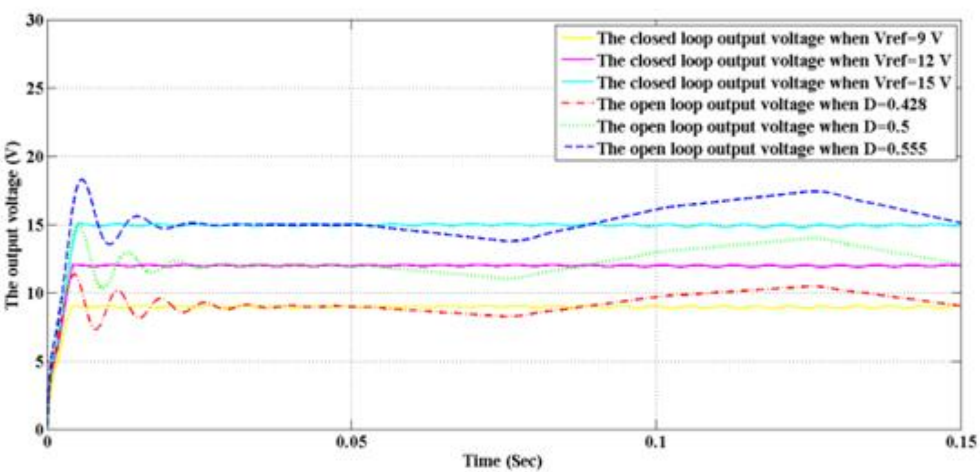


Figure 16 FLC closed loop and open loop systems responses with voltage source disturbance

The response of the three closed-loop and open-loop Zeta converter systems with voltage source disturbance is shown in Figure 16.

It is clearly shown that the open-loop response is greatly affected by the voltage source changes in terms of the large variations in the open-loop output voltage. On the other hand, the FLC closed loop system handles and controls these variations efficiently.

C.3 The System Analysis with both the Load and the Voltage Source Disturbances

In the real implementation of the Zeta converter system, both the load and the voltage source disturbances are expected to occur simultaneously, and this is the worst case scenario for the Zeta converter system.

The response of the three open loop and the three closed-loop Zeta converter systems for a simulation time $t = 0.15$ sec with both types of disturbances is illustrated in Figure 17. The disturbances in this case were changed linearly in the same manner explained previously.

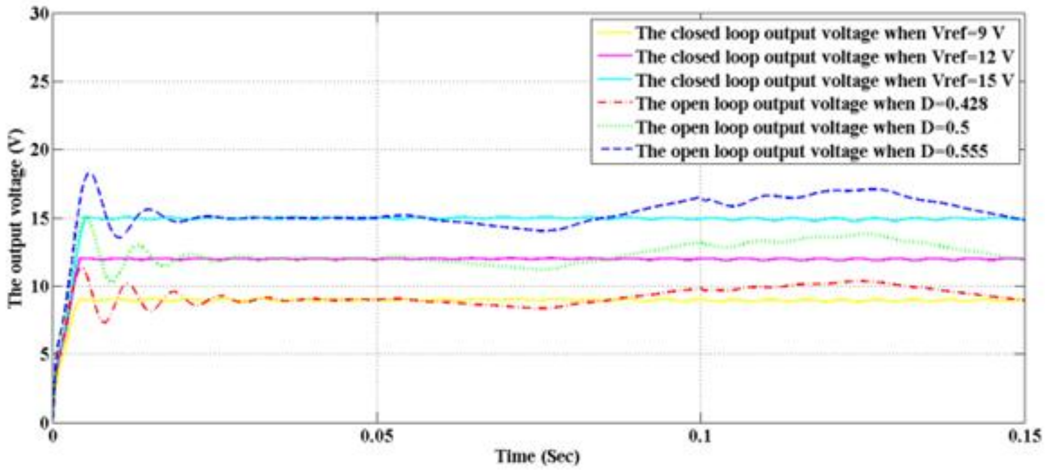


Figure 17 FLC closed loop and open loop systems responses with both disturbances

Thus, we may conclude that the designed fuzzy logic controller (FLC) handles and controls the response of the worst case of disturbances efficiently.

C.4 HYBRID FLC/BFO CONTROLLER DESIGN

In this section, V_O is limited to 15 V as the worst case scenario for simulating results. Furthermore, our results in this section will be compared with the results from the work of Ahmad, et.al [8].

The designed hybrid FLC/BFO controller is simulated considering both types of disturbances are present, and in which the FLC scaling gains will be tuned using the BFO algorithm. Table 7 illustrates the parameters used in the BFO algorithm.

TABLE 7
The BFO algorithm parameters

The BFOA parameters	
Symbol	**Value**
P	3
S	16
N_C	25
N_S	4
N_{re}	4
N_{ed}	2
P_{ed}	0.25

The BFO algorithm is implemented by MATLAB/SIMULINK using three MATLAB m-files: the first m-file is the BFOA main code; the second m-file is a function to run the Zeta converter system with each bacterium which is a trial solution, that computes its fitness or performance using the fitness function which is the integral of the absolute value of the error or IAE; and the third m-file is the cell to cell attraction function to simulate the swarming behavior of the bacteria in the population.

The used fitness function is as follows:

$$J = IAE = \int_{0}^{0.15} |e| \, dt \qquad (10)$$

The response of the closed loop Zeta converter system and the reference voltage V_{Ref} =15 V for a simulation time $t = 0.15$ sec with both types of disturbances, previously applied, is illustrated in Figure 18.

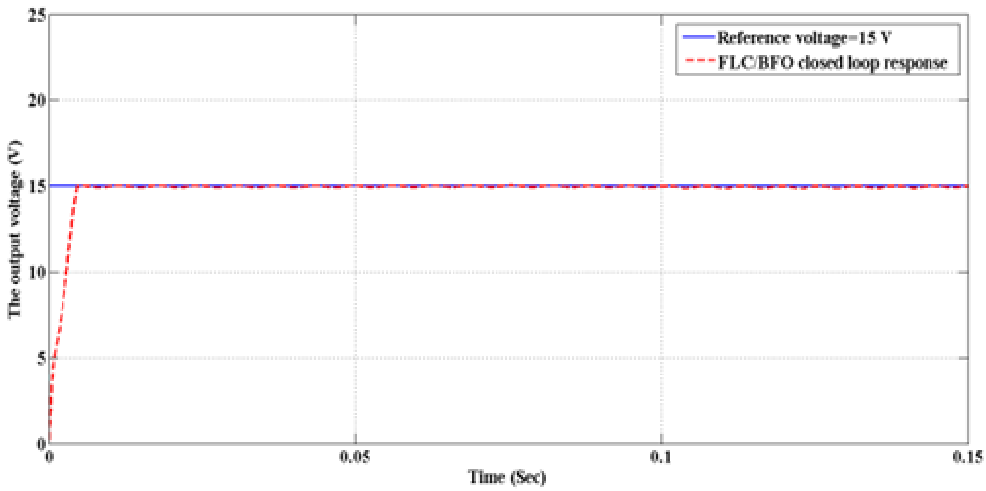


Figure 18 The closed loop Zeta converter response using the FLC/BFO controller

Table 8 illustrates the performance of the normal closed loop FLC/BFO Zeta converter system when V_{Ref} =15 V compared with the normal open loop and FLC closed loop systems.

TABLE 8
Zeta converter system performance comparison for different system designs, V_{Ref} =15 V

System design	Zeta converter systems performance comparison for different normal system designs			
	OS (%)	t_S (ms)	e_{SS} (%)	V_O ripples (V)
Open loop system	22.15	14.7	0.22	0.66
FLC closed loop system	0.50	4.15	0.9	0.153
FLC/BFO closed loop system	0.39	4.52	0.5	0.1518

First if we compare our designs with one another, table 8 shows that the FLC/BFO controller handles and controls the load and the voltage source disturbances more efficiently than the other controller types developed in this work. The performance of the FLC/BFO closed loop controller, when compared to the FLC closed loop controller, improved the overshoot by 22%, the steady state error by 44%, and the output voltage ripples by 0.8%. However, there was a 9% increase in the settling time as a direct result of decreased overshoot, owing to the increased damping introduced to the system, which naturally increases the settling time. When comparing our results with the results of Ahmad, et.al [8], we note that they made simulations of Zeta converter system using 9, 12, and 15 V as output voltages for the open loop system when the input voltage V_S = 12 V. They also used 9, 12, and 15 V as reference voltages for the FLC closed loop system, and they optimized the scaling gains of the FLC using Particle Swarm Optimization Algorithm (PSO) which resulted in designing the hybrid FLC/PSO controller. The Zeta converter circuit parameters used in [8] are illustrated in Table 9.

TABLE 9

The system parameters used in [8]

The Zeta converter system parameters used in [8]	
f	5 kHz
R	10 Ω
L_1	0.5 mH
L_2	0.5 mH
C_1	900 μF
C_2	1000 μF

As previously discussed, Table 3 illustrated the critical limits of L_1, L_2, C_1, and C_2 when $f = 5\,KHz$ and $R = 10\,\Omega$. Thus, from Table 9, we can conclude that the selected values for L_1 and L_2 in [8] did not satisfy the critical limits. These critical limits guarantee that the currents in L_1 and L_2 are increasing and decreasing linearly which guarantee that the average current in the load R is equal to the average current in the output inductor L_2.

On the other hand, Table 10 compares our results with Ahmad, et.al [8] results for the normal systems when V_{Ref} = 15 V.

TABLE 10

System performance comparison between our results and Ahmad, et.al [8] for V_{Ref}=15V

Zeta converter systems performance comparison for different normal system designs						
System design	Ahmad, et.al [8]			Our design		
	OS (%)	t_s (ms)	e_{ss} (%)	OS (%)	t_s (ms)	e_{ss} (%)
Open loop system	51.7	38	6.7	22.15	14.7	0.22
FLC closed loop system	2.7	7	0.47	0.50	4.15	0.9
FLC/PSO closed loop system	0.91	5	0.4	---		
FLC/BFO closed loop system	---			0.39	4.52	0.5

Thus, we can conclude that our work compared with Ahmad, at.al [8] gave better results where all of the critical limits of the Zeta converter system parameters were satisfied, the open loop system performance was very good in terms of the overshoot, settling time, and steady state error; our designed FLC clearly improved the open loop performance, and the BFOA for the hybrid FLC system gave better results than PSO with regards to the overshoot and the settling time. The steady state errors in our results in the FLC closed loop and the hybrid FLC systems were close to the steady state errors in [8].

VII CONCLUSION AND FUTURE WORK

In this paper, the simulations of the open loop Zeta converter system, the designing of a FLC and a hybrid FLC/BFO controllers were performed under MATLAB/SIMULINK environment for the nominal values and for different working conditions such as the load disturbance, the voltage source disturbance, or both for the different output converted voltages 9, 12, and 15 V when the voltage source was 12 V.

The FLC using Mamdani inference system performed better than the open loop performance, in which it improved the overshoot, the settling time, and the output voltage ripples with a very small increase in the steady state error for the different output converted voltages and the different working conditions.

The hybrid FLC/BFO controller performed better than the FLC controller, in which it added improvements to the overshoot, the steady state error, and the output voltage ripples with a very small increase in the settling time.

A comparison between our results and Ahmad, et.al [8] results which used the FLC/PSO controller for the reference voltage 15 V was performed. The comparison led to conclude that our results were better in terms of the overshoot and the settling time for the open loop systems, the FLC closed loop systems, and the hybrid FLC controller. The steady state error in our results for the open loop systems was better than in [8], while in the FLC closed loop and the hybrid FLC systems, the steady state error was close to the steady state error in [8]. Thus, we may conclude that BFOA is competitive in comparison with the PSO in which it presented better and more competitive results in the hybrid FLC system.

Future work may include: using the BFO algorithm to optimize the rule base component or the membership functions of the FLC, using the improved BFO (IBFO) algorithm, using Sugeno inference system in the FLC design, using type-2 fuzzy logic system in the FLC design, or using other optimization algorithms with the FLC such as Genetic Algorithm (GA) or Ant Colony Optimization (ACO) algorithm.

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