

Design and Implementation of Controlled Zeta Converter Power Supply

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Abstract This work includes Zeta voltage converter controller design and implementation. The mathematical model of the zeta converter circuit operating in the continuous conduction mode in state-space form is presented. Fuzzy Logic controller and hybrid Fuzzy Logic controller/ particle swarm optimization techniques are used to designed controller. Analysis and comparison between simulation and practical responses of open loop, close loop fuzzy logic controller and hybrid fuzzy logic/particle swarm optimization controller results are performed for different, working conditions such as sudden changes in the load resistance and reference voltages. The results show that there are significant improvement in the results for the proposed hybrid FLC/PSO control technique.

Keywords: Fuzzy Logic Controller (FLC), Particle Swarm Optimization (PSO), Zeta Converter

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1. Introduction

A DC-DC converter is widespread in modern portable electronic equipments and systems. The batteries are providing constant input voltage to the converter, then the converter converts it into wide range of values depending on the charge level. At low charge level, the voltage may drop below the battery voltage for continuously supplying the load with constant voltage [1,2]. There for it needs to be regulated. There are many research works dealing with the direct voltage converters performances and their control. One of those works was that of (A. H. Ahmed .et, al) in 2006 A.C [3]. They designed and analyzed a regulated controller of Cuk converter using H_{∞} / μ technique. O. A. Taha in 2007A.C[4] had studied CUK converter circuit performances, its designed and implement a robust controller for the cuk converter using H_{∞} synthesis technique. He studied the effects of CUK converter parameters changes on the circuit stability. S. S.Sabri in 2008 A.C, he studied the CUK converter circuit performance and designed controller for it using Fuzzy Logic Controller based genetic algorithm to improve its performance [5]. E. Vuthchhay and C. Bunlaksanusorn in 2010A.C [6]. They studied zeta converter circuit performance, Modeling and Control of the converter performance. R. Suresh Kumar, had studied BOOST converter circuit performance and its control using PID controller. He used a particle swarm optimization technique for the design and improvement of its performance [7]. Because of the lack of the studies about the ZETA converter circuit, the present work is dealing

with the design of the Fuzzy Logic Controller and hybrid Fuzzy Logic/ Particle Swarm Optimization Controller to control converter circuit output voltage and improve its output performance.

2. Zeta Converter Mathematic Model

The dc-dc voltage Zeta converter is assumed to operate in the continuous conduction mode(CCM).There exist two circuit states within one switch period T. First state is when switch is turned on (DT),and another when it is turned off [(1-D)T].The general state space mathematical model of the zeta converter is given by:

$$x' = Ax + Bu \quad (1)$$

$$y = Cx + Eu \quad (2)$$

Where

x: is $n \times 1$ state vector; A: is $n \times n$ system matrix; u:is $m \times 1$ input vector;

B: is $n \times m$ input matrix; E: is $L \times m$ matrix; y : is $L \times 1$ output vector; C: is $L \times n$ output matrix;

The zeta converter circuit is shown in Figure 1. It consists of IGBT transistor as a switch, Diode, two capacitors C_1 and C_2 , two inductors L_1 and L_2 with internal resistances r_1 and r_2 respectively and load resistor R_L . In the first mode of operation, the converter circuit(switch is ON) shown in Figure 2. During the interval (DT), the inductors L_1 and L_2 are in charging state[6].

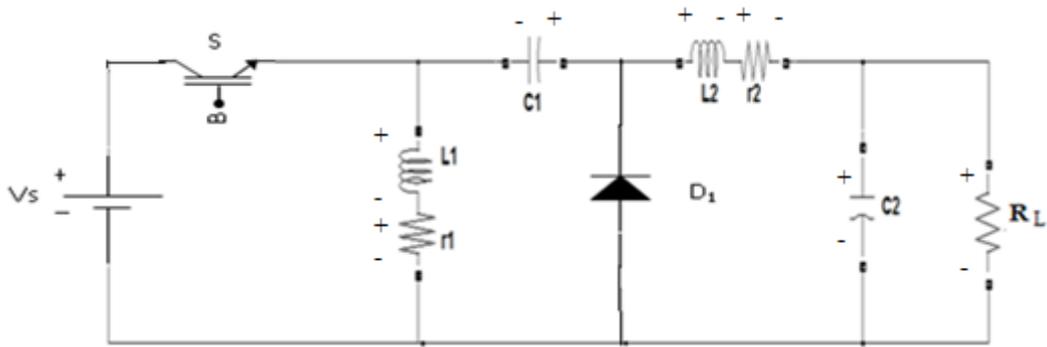


Figure 1. Zeta converter circuit

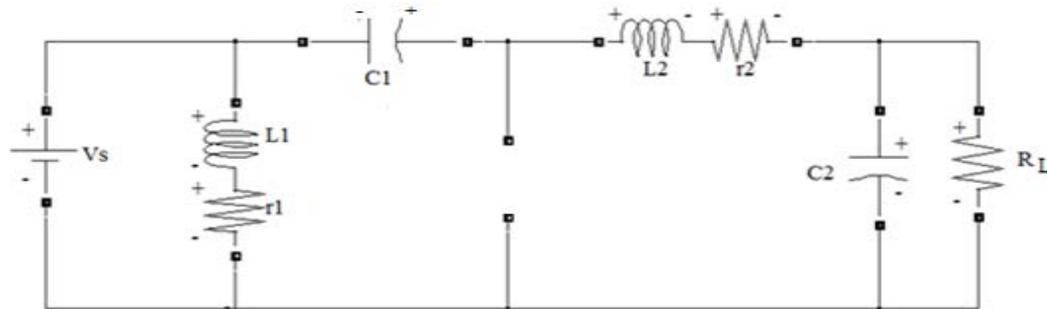


Figure 2. Mode one of Zeta converter circuit

Considering :

$$i_{L1} = x_1, i_{L2} = x_2$$

$$V_{C1} = x_3, V_{C2} = x_4$$

Applying the Kirchhoff's voltage law to the circuit in Figure 2 and writing the voltage equations for the open loop circuit and rearranging the equations to be in the state space form. The system equations became to be:

$$\frac{di_{L1}}{dt} = \frac{1}{L_1} \cdot v_s - \frac{r_1}{L_1} \cdot i_{L1} \quad (3)$$

$$\frac{dv_{C1}}{dt} = -\frac{1}{C_1} \cdot i_{L2} \quad (4)$$

$$\frac{di_{L2}}{dt} = \frac{1}{L_2} \cdot v_{C1} + \frac{1}{L_2} v_s - \frac{r_2}{L_2} \cdot i_{L2} - \frac{1}{L_2} \cdot v_{C2} \quad (5)$$

$$\frac{dv_{C2}}{dt} = \frac{1}{C_2} \cdot i_{L2} - \frac{1}{RC_2} \cdot v_{C2} \quad (6)$$

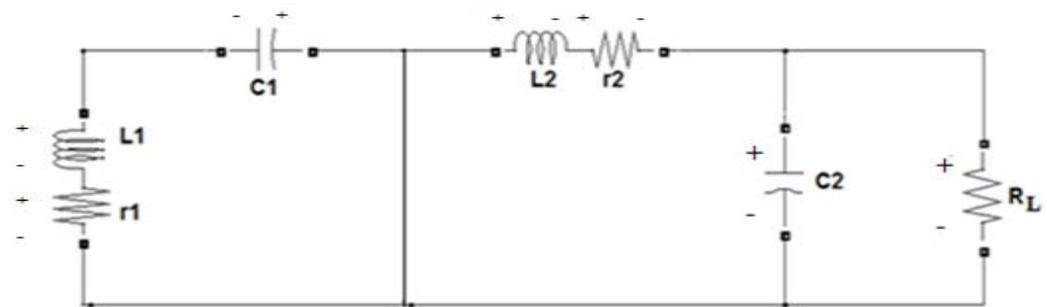


Figure 3. Mode two of Zeta converter circuit

In the second mode of operation (1-D)T the IGBT transistor is OFF. The converter equivalent circuit is shown as in Figure 3. In this mode the inductors (L_1, L_2) are in the discharging state. L_1 is discharging its stored energy into the capacitor C_1 , and the inductor L_2 transform energy to output section [6,8]. Then by the same way the system equations became to be:

$$\frac{di_{L1}}{dt} = \frac{r_1}{L_1} \cdot i_{L1} - \frac{1}{L_1} \cdot v_{C1} \quad (7)$$

$$\frac{dv_{C1}}{dt} = \frac{1}{C_1} \cdot i_{L1} \quad (8)$$

$$\frac{di_{L2}}{dt} = -\frac{1}{L_2} \cdot v_{C2} - \frac{r_2}{L_2} \cdot i_{L2} \quad (9)$$

$$\frac{dv_{C2}}{dt} = \frac{1}{C_2} \cdot i_{L2} - \frac{1}{RC_2} \cdot v_{C2} \quad (10)$$

Using on state and off state equation, the system state space equivalent equation became to be:

$$\begin{bmatrix} \bar{x}_1 \\ \bar{x}_2 \\ \bar{x}_3 \\ \bar{x}_4 \end{bmatrix} = \begin{bmatrix} -\frac{r_1}{L_1} & 0 & \frac{D-1}{L_1} & 0 \\ 0 & -\frac{r_2}{L_2} & \frac{D}{L_2} & -\frac{I}{L_2} \\ \frac{1-D}{C_1} & -\frac{D}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_3} & 0 & -\frac{1}{RC_3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \frac{D}{L_1} \\ \frac{D}{L_2} \\ 0 \\ 0 \end{bmatrix} u \quad (11)$$

$$y = [0 \ 0 \ 0 \ 1] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \quad (12)$$

The relation between input and output voltages of the zeta converter is given by:

$$V_o = \frac{D.V_s}{(1-D)} \quad (13)$$

3. Zeta Converter Circuit Design

Applying Kirchhoff's voltage law on Zeta converter circuits: first and second modes. The produced ripple inductors currents and ripple capacitor voltages are given by the equations below:

$$\Delta I_1 = \frac{DV_s}{FL_1} \quad (14)$$

$$\Delta I_2 = \frac{DV_s}{FL_2} \quad (15)$$

$$\Delta V_{C1} = \frac{DV_s}{8F^2C_1L_1} \quad (16)$$

$$\Delta V_{C2} = \frac{DV_s}{8F^2C_2L_2} \quad (17)$$

Where: F is the switching frequency (F=5Khz), $\Delta I_1 = 2.5A$, $\Delta I_2 = 2.5A$, $\Delta V_{C1} = 0.06V$, $\Delta V_{C2} = 0.06V$, $D=0.5$.

From the equations above the critical values of the inductors and capacitors of the Zeta converter circuit may be introduced as the follows: [6]

$$L_1 \geq \frac{(1-D)^2 R_L}{2DF} \quad (18)$$

$$L_2 \geq \frac{(1-D)R_L}{2F} \quad (19)$$

$$C_1 \geq \frac{D}{8F(1-D)R_L} \quad (20)$$

$$C_2 \geq \frac{1}{8FR_L} \quad (21)$$

Whereas the above components became to be: $L_1 = 0.5mH$, $L_2 = 0.5mH$, $C_1 = 900\mu F$, $C_2 = 1000\mu F$.

4. Fuzzy Logic Controller Design

Fuzzy logic controller has been designed for writing its inputs as : The error e(t) and the error change $\Delta e(t)$ of the output voltage. The linguistic variables are defined as (N, NS, Z, PS, P) where N means negative, NS negative small, Z zero, PS positive small, P positive. Triangular membership functions of the fuzzy logic controller are considered. The fuzzy rules are summarized in Table 1. The surge no type of fuzzy inference engine is considered [5]. The error range are taken between (-30 and 30) as shown in Figure 4a, and range of error change are taken between (-12 and 12) as shown in Figure 4b.

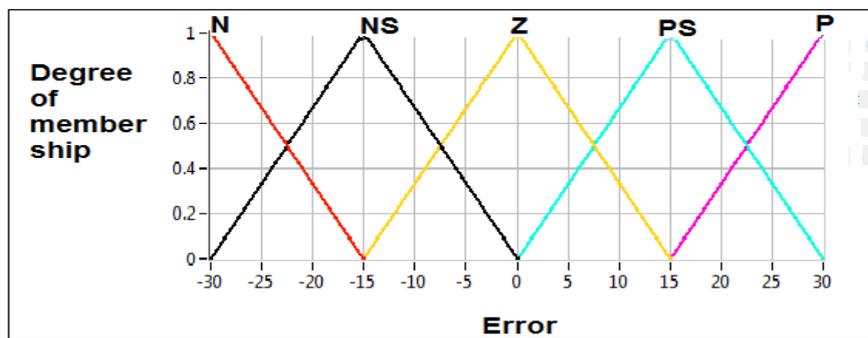


Figure 4a. The error membership function

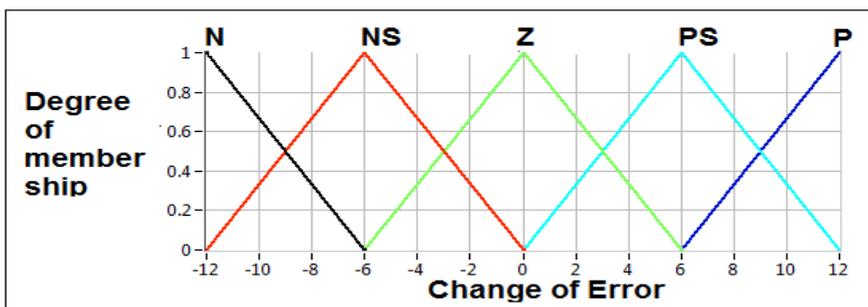


Figure 4b. The change of error membership function

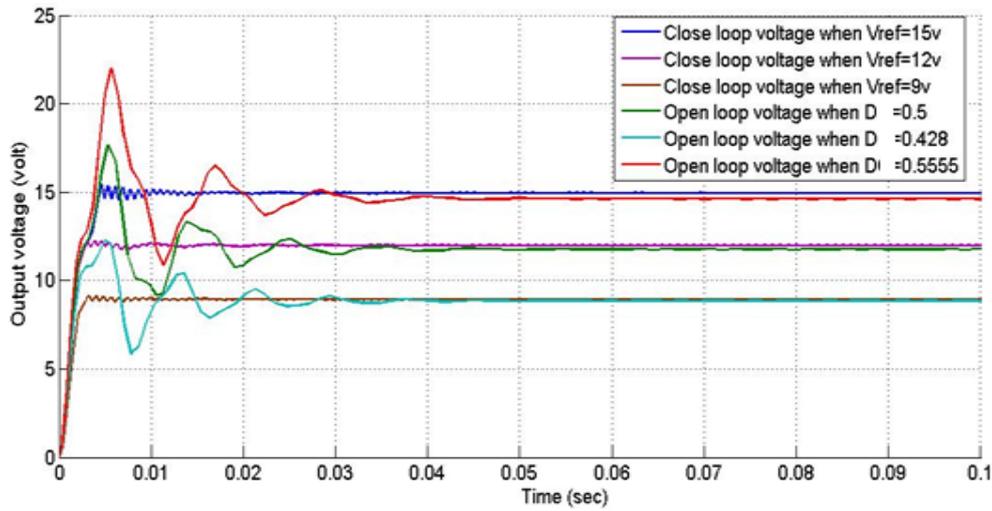


Figure 5. output voltage responses of the open loop and closed loop systems with FLC when Vref =9,12 and15 volts and R_L (10) Ω

Table 1. Fuzzy Logic Controller rule base

e/ Δe	N	NS	Z	PS	P
NB	N	N	N	NS	Z
NS	N	N	NS	Z	PS
ZE	N	NS	Z	PS	P
PS	NS	Z	PS	P	P
PB	Z	PS	P	P	P

The output voltage responses for the open loop and closed loop systems with Fuzzy Logic Controller are shown on the same graph in Figure 5 for reference voltages (9,12 and15) volts and load resistance (10) Ω .

5. Particle Swarm Optimization Algorithm

Particle swarm optimization technique, first developed by (J. Kennedy and R. Eberhart, 1995) as one of the modern heuristic algorithms. It was inspired by the social behavior of the bird and fish schooling and has been found to be robust in solving continuous nonlinear optimization problems [7,9]. This algorithm is based on the following scenario: a group of birds are randomly searching for food in an area and there is only one piece of food. All birds are unaware where the food is, but they do know how far the food is at each time instant. The best and most effective strategy to find the food would be to follow the bird which is nearest to it. Based on such scenario, the PSO algorithm is used to solve the optimization problem.

In PSO, each single solution is a “bird” in the search space; this is referred to as a “particle”. The swarm is modeled as particles in a multi-dimensional space, which have positions and velocities. These particles have two essential capabilities: their memory of their own best position and knowledge of the global best. Members of the swarm communicate good positions to each other and adjust their own position and velocity based on good positions according to following equations (22,23): [7,10].

Let:

i to be the number of particles

j to be the number of iterations

$$v(k+1)_{i,j} = w.v(k)_{i,j} + C_1r_1(gbest - x(k)_{i,j}) + C_2r_2(pbest_i - x(k)_{i,j}) \tag{22}$$

$$x(k+1)_{i,j} = x(k)_{i,j} + v(k+1)_{i,j} \tag{23}$$

Where as:

$v(k)_{i,j}$ is velocity of the particle i

$x(k)_{i,j}$ is position of the particle i

C_1, C_2 are the acceleration constants

W is the inertia weight factor

r_1, r_2 are random numbers between 0 and 1

$Pbest$ is the best position of the specific particle

$Gbest$ is the best particle of the group.

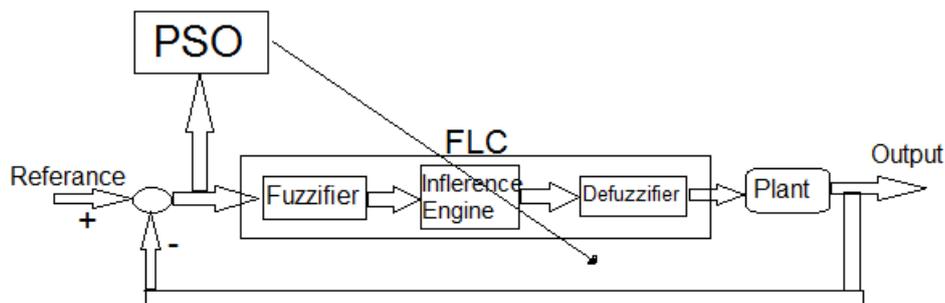


Figure 6. system block diagram

6. Hybrid Fuzzy Logic /Particle Swarm Optimization Controller Design

The design of an optimal fuzzy logic controller is performed using the PSO algorithms to search globally its optimal gains. The structure of the fuzzy logic controller

with PSO algorithms is shown in Figure 6. The optimization algorithm is implemented by using MATLAB m-file program and linked with the system simulation program in MATLAB/SIMULINK, to check the system performance in each particle. The PSO produces the FLC controller gains which give optimal performance for the Zeta converter. The minimum

absolute integral error is adopted in this work, which is given by the following equation (20).

$$ISE_{min} = \frac{1}{N} \sum_{i=1}^N |V_r - V_{act}(i)| \quad (24)$$

When n: is number of samples considered.

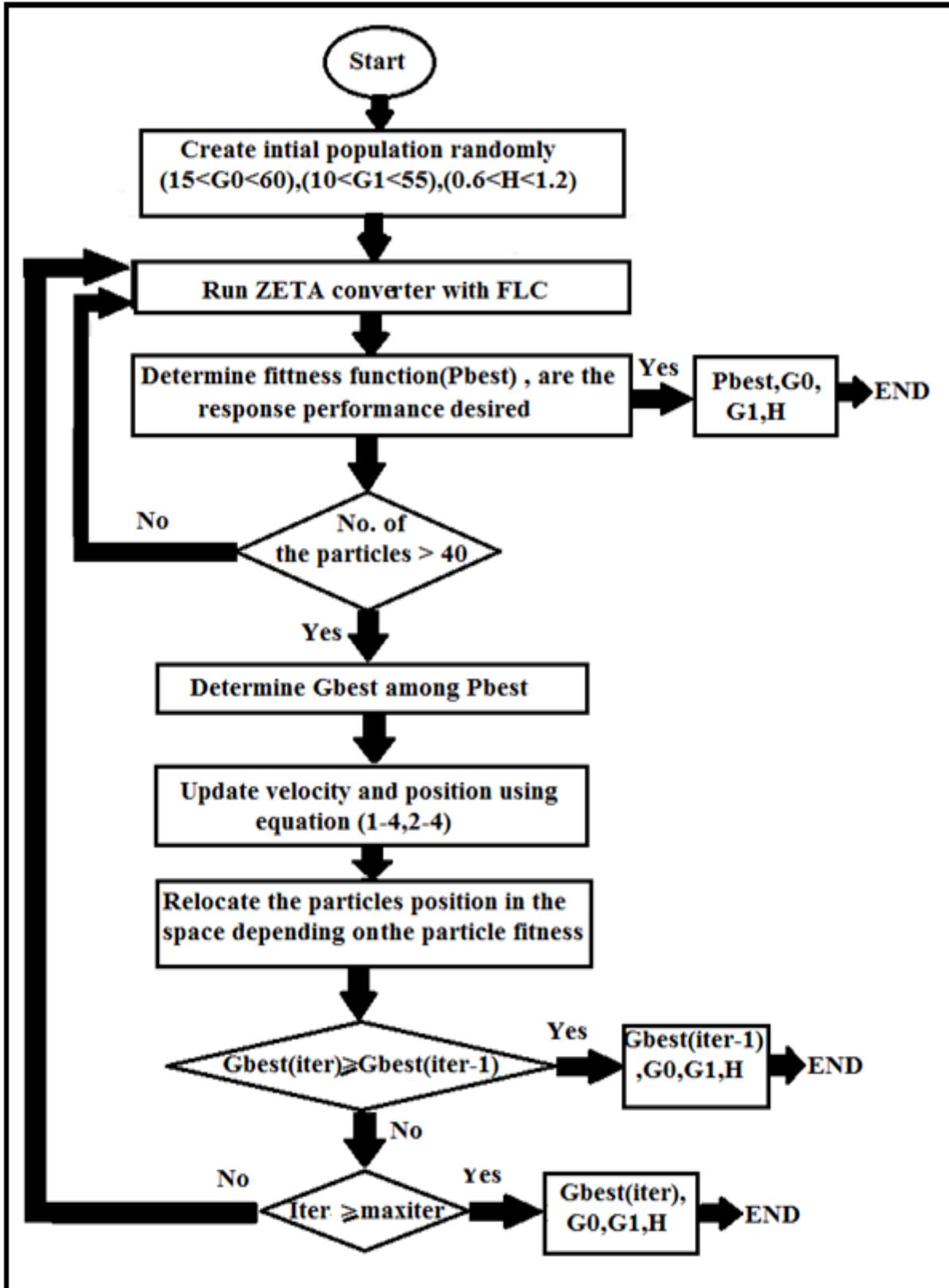


Figure 7. FLC / PSO flowchart

The PSO technique has been programmed using MATLAB M-file. PSO algorithm is used in this work to compute the fuzzy controller gains $G, G1, H$ during the system disturbance, the error information reaches the PSO algorithm. Then, it starts to update the fuzzy gains values for maintaining the desired system performance..The hybrid FLC/ PSO flowchart is shown in Figure 7.

7. System Realizationz

The system is implemented practically as open loop, closed-loop with FLC and hybrid FLC/ PSO as shown in Figure 8. The open-loop voltage response when duty ratio ($D=0.5555$) and load resistance ($R_L = 10-40-10\Omega$) is shwon in Figure 9. The close loop voltage response with FLC when referance voltage ($V_{ref}=15$ volt) and load resistance ($R_L = 10\Omega$) is shwon in Figure 10. The close loop voltage response with hybrid FLC/ PSO when referance voltage ($V_{ref}=15$ volt) and load resistance ($R_L = 10\Omega$) is shwon in Figure 11.

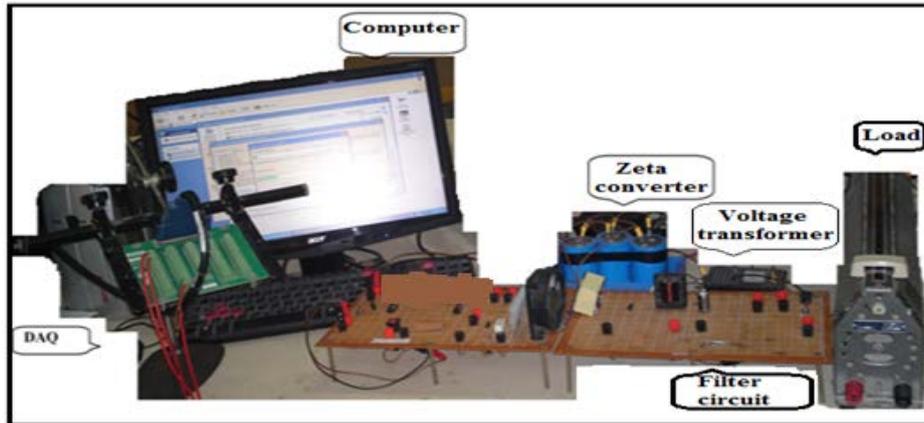


Figure 8. Practical system

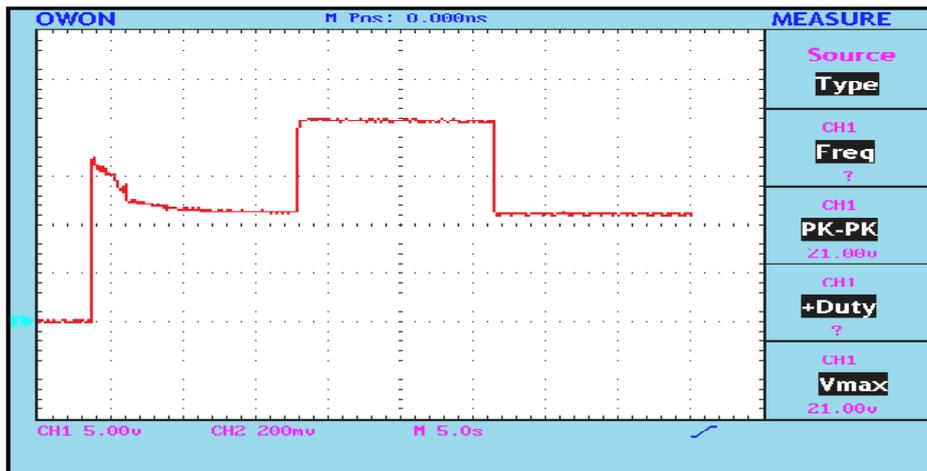


Figure 9. output voltage response of the open loop when ($D=0.5555$) and ($R_L = 10-40-10 \Omega$)

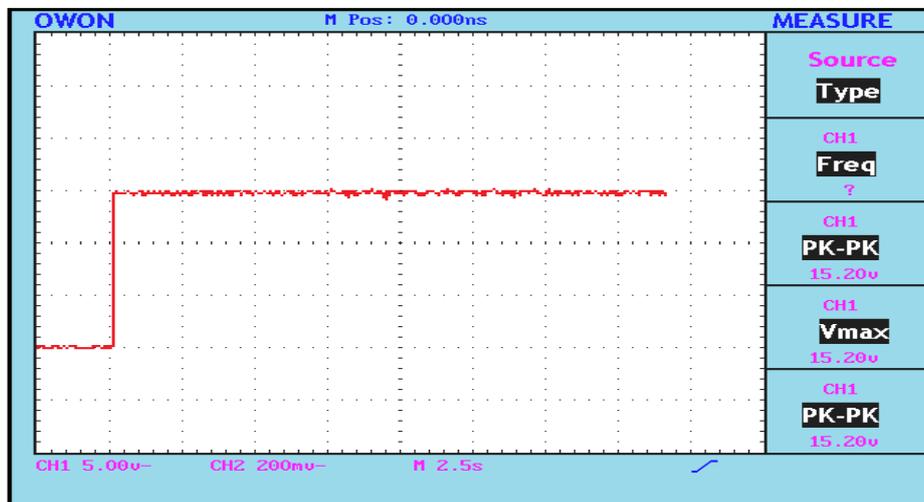


Figure 10. output voltage response of the closed loop system with FLC for V_{ref} 15 volt and ($R_L = 10-40-10 \Omega$)

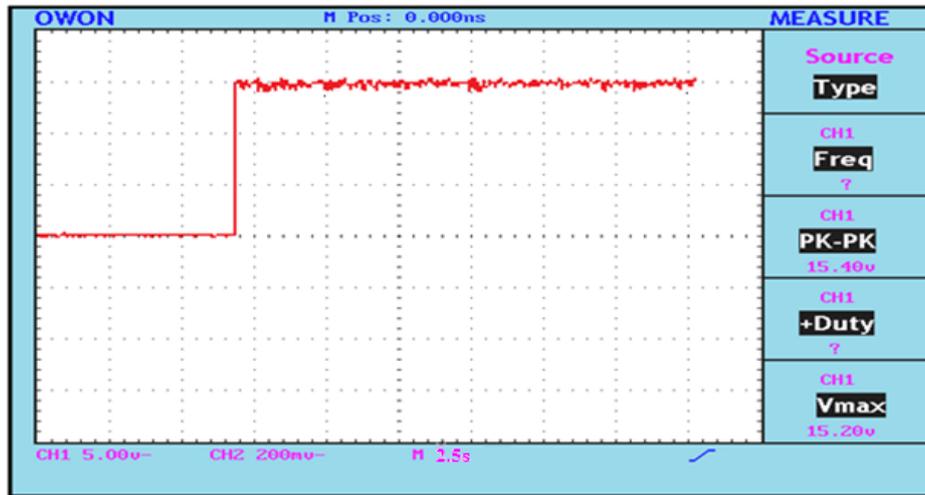


Figure 11. output voltage response of the closed loop system with hybrid FLC/PSO for $V_{ref} = 15$ volt and ($R_L = 10-40-10 \Omega$)

8. Results and Discussion

The output voltages for the simulated open loop and closed loop systems with fuzzy logic controller are shown in Figure 12, for reference voltages (9, 12 and 15) volt, for varying the load resistance ($10-40-10 \Omega$) at time ($t=0.05-0.1-0.15$ sec) respectively. The fuzzy logic controller gains are chosen by trial and error method to get the best zeta converter output performance. This process needed long time. The closed loop system with the FLC/PSO controller response shown in Figure 13 has great improvement in it

performance of the absolute integral error was minimum. It overcame the problem of long time manual tuning. The output voltage of the closed loop system with FLC had been adapted using PSO technique when reference voltages (9, 12 and 15) volts and varying load resistances equal to ($10-40-10 \Omega$) as shown in Figure 13. The closed loop practical system response with FLC/ PSO when reference voltages (9-12-15 volt) and load resistance (10Ω) is shown in Figure 14. Comparison between theoretical and practical results for open loop, close loop with FLC and hybrid FLC/PSO controller for voltage (15 volt) are shown in the Table 2.

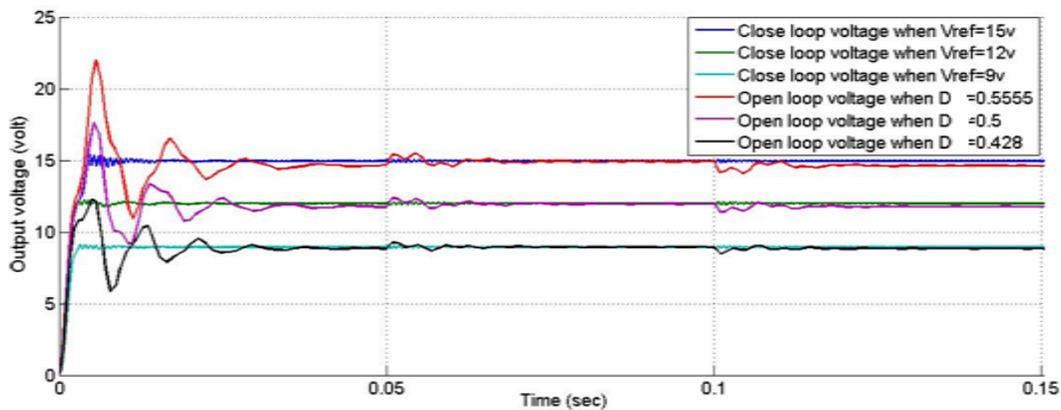


Figure 12. open loop system and close loop system with FLC controller responses for $V_{ref} = 9, 12, 15$ volts and $R_L = 10-40-10 \Omega$

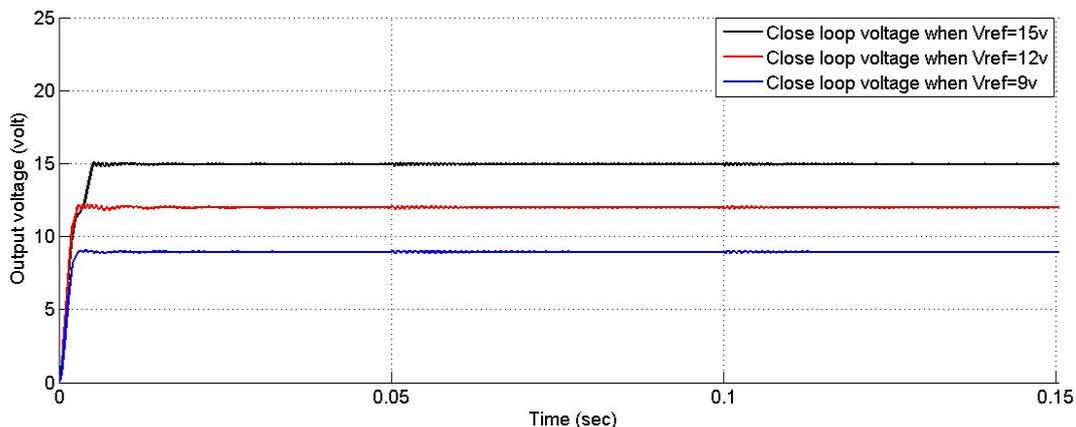


Figure 13. close loop system with FLC/ PSO controller responses for $V_{ref} = 9, 12, 15$ volts and $R_L = 10-40-10 \Omega$

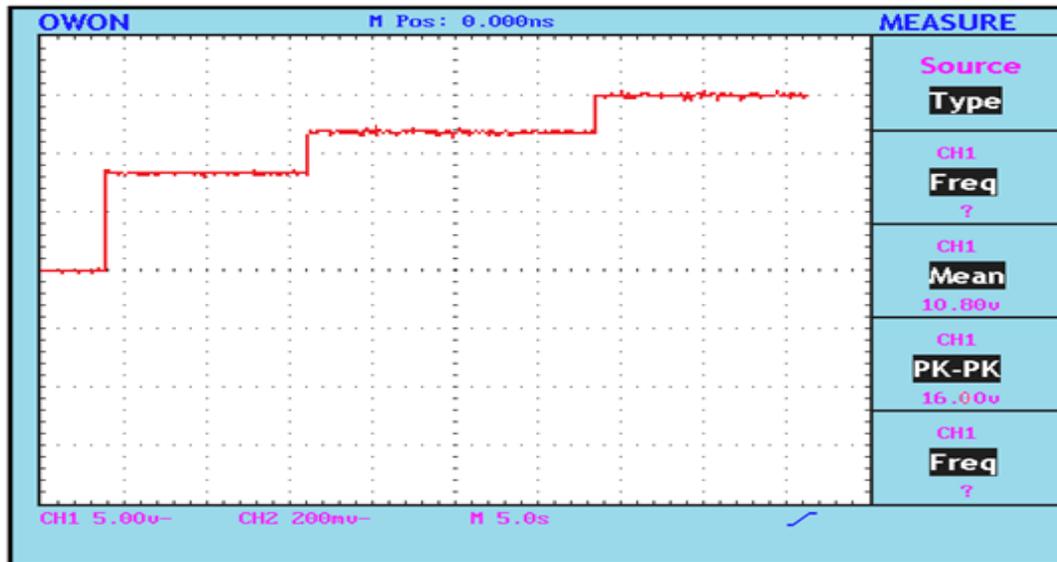


Figure 14. output voltage response of the closed loop system for $V_{ref} = 9,12,15$ volts and $R_L (10) \Omega$.withFLC /PSO controller

Table 2. Comparison of the system performance for the different techniques when reference voltage ($V_{ref}=15$ volts)

Design system	Steady state error[%]	Peak Overshoot [%]	Settling time[ms]
Zeta converter circuit theoretically	6.7	51.7	38
Close loop system with FLC	0.47	2.7	7
Close loop system with FLC /PSO	0.4	0.91	5
Zeta converter circuit practically	16.7	49	312
Close loop system with FLC practically	0.49	2.9	22
Close loop system with FLC / PSO practically	0.43	0.95	13

From Table 2 above, it is shown that the performance of the converter for open loop system has high peak overshoot, the steady state time and state steady error. The system manually optimized fuzzy controller gains response performance (P.O.S, t_{ss} and e_{ss}) have been improved. Hybrid FLC/PSO (P.O.S, t_{ss} and e_{ss}) has improvements. The realized system response performance appears verified the theoretical ones except the steady state time witch was slightly higher. Comparison of the results show that the proposed(FLC/PSO)control is the best.

9. Conclusion

Zeta converter circuit has been designed. Its mathematical model in state space form has been developed. The circuit output voltage response as an open-loop system has been analyzed. Two techniques has been use to regulate the output voltage of the zeta converter circuit. Fuzzy logic controller technique has been used. Hybrid fuzzy logic /particle swarm optimization technique has been proposed. The output voltage for the Zeta converter with the feedback controller and two technique has been studied. It has been seen that the response of the Zeta converter circuit with the proposed technique was better than that of FLC technique. The computation time for the FLC/PSO gains were very short. The designed circuit with the controllers was implemented. The practical results was verified the simulated results. Therefore one can conclude that the proposed method is the best one.

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