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Particle Swarm Optimization based Fuzzy Logic Controller for Luo Converter

N. Nachammai[1], R. Kayalvizhi[2],
[1,2]*Department of Electronics and Instrumentation Engineering, FEAT, Annamalai University*

Abstract**: Negative output elementary Luo converter performs the conversion from positive DC input voltage to negative DC output voltage. Since Luo converters are non-linear and time-variant systems, the design of high performance controllers for such converters is a challenging issue. The controller should ensure system stability in any operating condition and good static and dynamic performances in terms of rejection of supply disturbances and load changes. To ensure that the controllers work well in large signal conditions and to enhance their dynamic responses, soft computing techniques such as Fuzzy Logic controller (FLC) and Particle Swarm Optimization based FLC (PSO-FLC) are suggested. In recent years, Fuzzy logic has emerged as an important artificial intelligence tool to characterize and control a system, whose model is not known or ill defined. Fuzzy logic is expressed by means of if-then rules with the human language. In the design of a fuzzy logic controller, the mathematical model is not necessary. However, the rules and the membership functions of a fuzzy logic controller are based on expert experience or knowledge database. To ensure better performance of fuzzy controller, membership functions, control rules, normalizing and de-normalizing parameters are optimized using PSO. The main strength of PSO is its fast convergence than the other global optimization algorithms. To exhibit the effectiveness of proposed algorithm, the performance of the PSO based fuzzy logic controller has been compared with FLC and the necessary results are presented to validate the PSO for control purposes. Comparative study emphasize that the optimized PSO based fuzzy controller provide better performance and superior to the other control strategies because of fast transient response, zero steady state error and good disturbance rejection under variations of line and load and hence output voltage regulation is achieved. Simulation studies have been performed using Matlab-Simulink software.

Keywords: Fuzzy Logic Controller, particle Swarm Optimization, Luo Converter, Membership Functions

I. INTRODUCTION

DC-DC converters are electronic devices used to change DC electrical power efficiently from one voltage level to another. These converters are widely used in switched-mode power supplies, adjustable speed drives, uninterruptible power supplies, telecommunication equipment, spacecraft power system etc. Fuzzy logic controller performs the control of nonlinear systems based on designer practical experience.

The application of this technique does not require accurate models of the converter and is able to deal with its typical nonlinearities, showing less sensitivity to noise disturbances and parameters variations. In recent years, several heuristic optimization techniques such as Differential Evolution (DE), Ant Colony Optimization (ACO) and Genetic Algorithm (GA) were introduced in the field of fuzzy control applications because of their fast computability.

Though GA-FLC approach performs well for complex optimization problems, recent research has identified certain problems where variables are highly correlated and GA crossover and mutation operators do not generate individuals with better fitness of offspring as the chromosomes in the population pool.

This research work presents an approach to overcome the design problem of GA-FLC by means of PSO-FLC. PSO algorithm has several advantages such as speed of convergence, simplicity of implementation and less susceptibility of being trapped in local optima. PSO has more actual memory ability than the GA, since each particle recalls its best value in previous iteration and the neighbourhood best. As all particles use the information related to the most successful particle in order to improve them, the algorithm is more effective in preserving the variety of the swarm.

The population evolves around a subset of the best individuals in PSO, since the poor solutions are discarded and only the good ones are preserved.

In this work, two types of controllers are designed namely the Fuzzy controller and PSO-Fuzzy controller. Fuzzy controller parameters were optimized by PSO for regulating the output voltage of Luo converter. Simulation results are compared and it is found that PSO outperforms random search and at the end of the search process, showing better convergence behaviour.

II. NEGATIVE OUTPUT ELEMENTARY LUO CONVERTER (NOELC)

The negative output elementary Luo converter circuit shown in Fig. 1 performs step-down and step-up DC-DC conversions. Switch S is a N-channel power MOSFET (NMOS) device. It is driven by a PWM switching signal with repeating frequency ‘f_s’ and duty ratio ‘d’. The switching period is $T = 1/f_s$ so that the switch-ON period is dT and the switch-OFF period is $(1-d)T$.

The elementary circuit can be considered as a combination of an electronic pump S-L_1-D-C and a π type low-pass filter C-L_2-C_0. The pump injects certain energy into the low-pass filter every cycle. Capacitor C acts as the primary means of storing and transferring energy from the source to the load.

When the MOSFET is ON, inductance L_1 absorbs energy from the source and the current i_{L_1} increases linearly with the slope V_I/L_1. At the same time, the diode D is blocked since it is reverse biased. Inductor L_2 keeps the output current I_O continuous and transfers energy from capacitor C to the load R. The equivalent circuit for the switch-ON period (Mode 1) is shown in Fig.2.

When the MOSFET is OFF, the source current $i_I = 0$. Current i_L flows through the freewheeling diode D to charge capacitor C and also enhance current i_{L_2}. Inductor L_1 transfers its stored energy to capacitor C and load R via inductor L_2. Thus the current i_{L_1} decreases. The equivalent circuit for the switch-OFF period (Mode 2) is shown in Fig.3. The voltage transfer gain in continuous conduction mode is $V_O / V_I = d / (1-d)$.

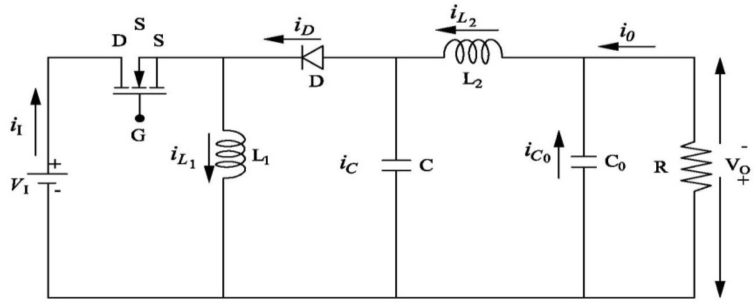

Fig.1 Circuit Diagram of Negative Output Elementary Luo Converter

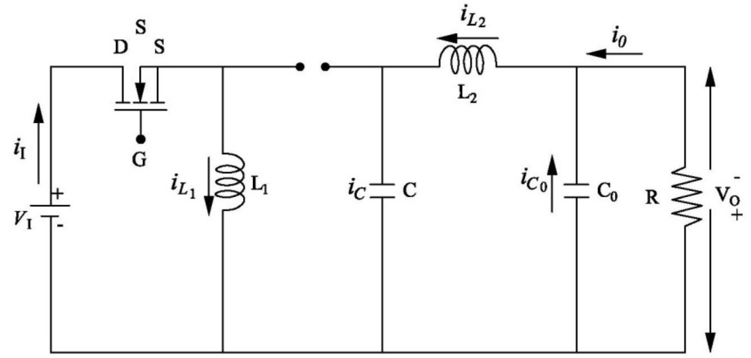

Fig. 2 Equivalent Circuit during Switch-ON (Mode l)

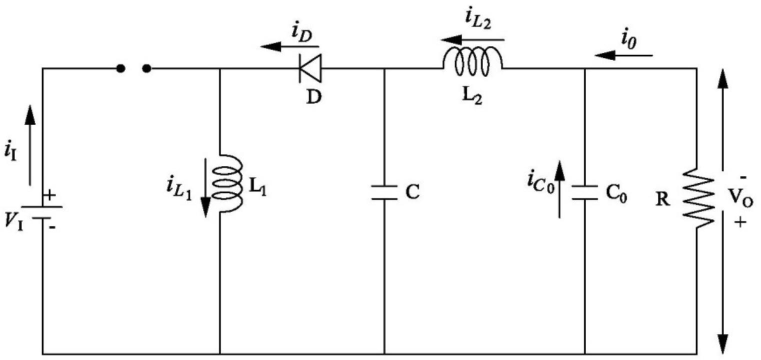

Fig. 3 Equivalent Circuit during Switch-OFF (Mode 2)

III.FUZZY LOGIC CONTROLLER

Fuzzy logic is a form of many-valued logic which is derived from fuzzy set theory. In contrast with "crisp logic", where binary sets have two-valued logic, fuzzy logic variables may have a truth value that ranges in degree between "0" and "1". Fuzzy logic controller is a control tool for dealing with uncertainty and variability in the plant. The implementation of the proposed controller does not require any specific information about the converter model as well as circuit parameters and works independent of the operating point of the Luo converter.

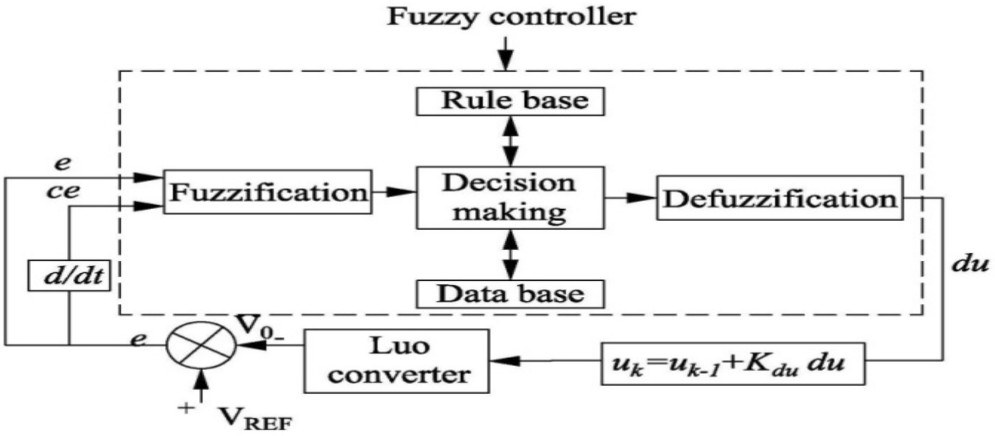

Fig.4Block Diagram of Fuzzy Logic controller for Luo converter

Design of fuzzy logic controllers mainly involves three steps, namely fuzzification, fuzzy rule base and defuzzfication which is shown in Fig. 4. Fuzzification is a process in which the inputs are fuzzified between a range of 0 to 1. Rule base is formed by the experts knowledge and depending on the inputs, the rule base generates the corresponding linguistic variable output. This output is defuzzified from 0 to 1 to a global value. The designed FLC has two inputs, error (*e*) and rate of change of error (*ce*) and a controller output (*du*). The number of necessary fuzzy sets and their ranges are designed based upon the experience gained on the process. A Mamdani based system architecture has been realized. Max-min composition technique and centre of gravity method have been used in the inference engine and defuzzification. In the present work, seven triangular fuzzy sets are chosen as shown in Fig. 5 and are defined by the following library of fuzzy set values for the error *e*, change in error *ce* and for the change in duty cycle *du*. NB: Negative Big, NM: Negative Medium, NS: Negative Small, Z: Zero, PS: Positive Small, PM: Positive Medium, PB: Positive Big. The fuzzy rule base consists of 49 rules which are used to produce change in duty cycle (du) of the MOSFET of the Luo converter

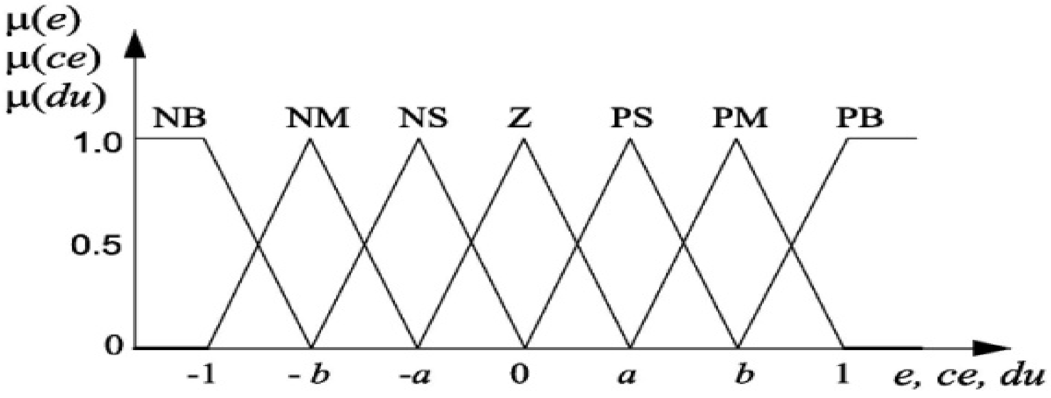

Fig. 5 Triangular Type Membership Functions for Error, Change in Error and Change in Duty Cycle

A rule table is derived and is shown in Table 1. The inference mechanism seeks to determine which rules fire to find out which rules are relevant to the current situation. The inference mechanism combines the recommendations of all the rules to come up with a single conclusion.

Since the inferred output is a linguistic value, a defuzzification operation is performed to obtain a crisp value. In this work, the centre of gravity or centroid method is used for de-fuzzification.

TABLE I
RILES FOR MAMDANI-TYPE FUZZY SUSTEM

e* \ *ce	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

IV. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization is a population based stochastic optimization technique, inspired by social behaviour of bird flocking or fish schooling. In PSO the individuals called particles, fly around in a multidimensional search space and change their position with time. During its flight, each particle adjusts its position according to its own experience and according to the experience of neighbouring particles. The position or value corresponding to its own experiences called pbest and corresponding to the experience of neighbouring particles is called gbest. The search for the optimal position advances as the velocities and positions of the particles are updated. The fitness of each particle's position and iteration is calculated using a pre defined objective (fitness) function and the velocity of each particle is updated using the pbest and gbest**,** which were previously defined. The velocity of ith particle can be modified by the eqn. 1. The values c_1 and c_2 are two positive constants represent the social and cognitive accelerations for the pbest and gbest positions, respectively. The flow chart of PSO algorithm is shown in Fig. 6.

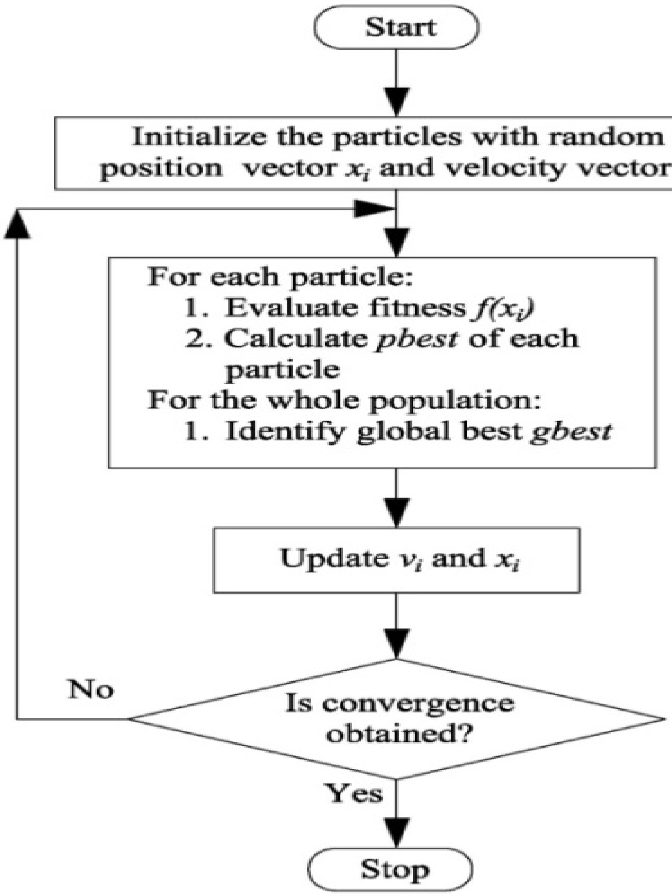

Fig. 6 Flow chart of PSO Algorithm

PSO Algorithm
Step 1 : Define fitness function.
Step 2 : Initialize the particles of the population according to the limits. Initialize parameters c_1, $c_2$and iter$_{max}$.
Step 3 : Generate the initial population of N particles with random positions and velocities.
Step 4: Calculate the fitness and evaluate the fitness values of current particle using the objective function ISE.
Step 5 Compare the fitness value of each particle with its *pbest*. If the current value is better than *pbest*, then set *pbest* value to the current value.
Step 6 Compare the fitness value of each particle with its *gbest*. If the current value is better than *gbest*, then set *gbest* value to the current value.
Step 7 The member velocity *v* of each individual in the population is updated according to the velocity update equation, as given in eqn. 1.

$$v_i^{(t+1)} = w\, v_i^{(t)} + c_1 r_1 \left(pbest_i - x_i^{(t)}\right) + c_2 r_2 \left(gbest - x_i^{(t)}\right) \qquad (1)$$

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \qquad (2)$$

$v_i^{(t+1)}$is the new velocity of the *i*thpatticle.

$v_i^{(t)}$current velocity of the *i*thpatticle.

w is the weight factor

$r_1$andr_2 are two random numbers between the range (0,1).

$c_1, c_2$are learning factors $0 \leq (c_1 + c_2) \leq 4$ In this work, $c_1 = c_2 = 2$.

$x_i^{(t)}$is the current position of the *i*th particle.

Step 8 The position of each individual is modified according to the position updated equation, as given below
New position = old position + updated velocity
Step 9 If the number of iterations reaches the maximum, then go to Step 10. Otherwise, go to Step 4
Step 10 The particle that generates the latest *gbest* is the solution of the problem.
Step 11 Stop.

V. PSO BASED FUZZY LOGIC CONTROLLER

The parameters representing the linguistic sets, scaling gains and fuzzy rules are represented by the optimization variable of the PSO, called particle. It is a vector of real numbers that consists of three parts, the first part is related to the real numbers required to identify the membership functions, the second part is related to the integer numbers required to identify the fuzzy rules and the third part is related to the real numbers to identify the scaling gains. With regards to the first part of the particle identifying the membership functions, a maximum number of seven fuzzy sets has been chosen. Tuning of the membership functions can be carried out by expanding or shrinking the membership functions in relation to its universe of discourse. As each linguistic variable has been assumed to have a maximum of seven primary terms, two parameters are then required to represent the membership functions of a linguistic variable of the implemented fuzzy controller. Therefore, in order to represent the three linguistic variables, six parameters are needed to characterize the search space of the problem. With regards to the second part of the particle identifying the fuzzy rules, a total of forty-nine fuzzy rules are used. FLC can be optimized by adjusting the scaling gains K_e, K_{ce} and K_{du}. Totally 58 parameters are required to design the fuzzy controller and are represented by the particle. PSO stops if any of the following conditions is reached:

A. The maximum generation number exceeds 100,
B. There is no improvement in the objective functions of the non- dominated solutions for 50 consecutive generations.

The number of the linguistic sets of the proposed controller has been determined by comparing the responses of the Luo converter for different numbers of the fuzzy sets. The fitness function has been compared for four, five and seven fuzzy sets. It has been found that the use of more than seven linguistic sets does not improve the performance of the converter but, indeed, increases the computation time. Consequently, for this research work, seven triangular membership functions have been considered for each input variable, seven linguistic sets have been chosen for the output variable of the fuzzy controller structure. The triangular membership function is chosen due to its simplicity. Integral square error (ISE) is used as an objective function. The mathematical equation of the ISE is given by

$$ISE = \int_0^T e^2(t)dt \qquad (3)$$

The structure of the fuzzy logic controller with PSO algorithm is shown in Fig. 7. In order to design the optimal fuzzy controller, the PSO algorithm is applied to search globally optimal parameters of the fuzzy logic controller. The performance of the system must be examined in each particle and iteration position during the optimization process. 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 fuzzy controller gains of the FLC which give optimal performance of the Luo converter. In this work, the particle of the PSO algorithm includes three parts: the scaling gains for e, ce, and du $(K_e, K_{ce}$ and $K_{du})$, the shape of the membership functions $(a_e, b_e, a_{ce}, b_{ce}, a_{du}, b_{du})$ and the fuzzy inference rules (C1, C2, ……….C49).

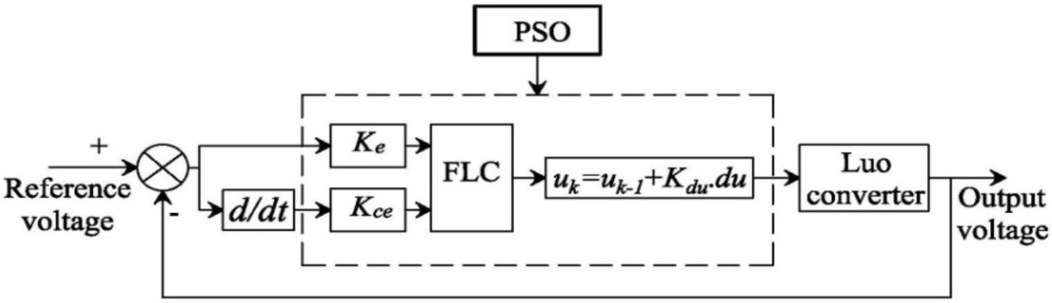

Fig. 7 Structure of FLC with PSO Algorithm

Table II lists the parameters of PSO algorithm used in this work Table IIIlists the fuzzy inference rules with PSO algorithm. Membership functions for inputs and output variables searched by PSO are shown in Fig. 8.

TABLE III
PARAMETERS OF PSO ALGORITHM

Parameter	Particle dimension	Swarm size	Number of iterations	c_1 and c_2
Value	58	30	100	2

TABLE IIIII
OPTIMISED FUZZY RULES

e \ ce	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	Z	PS
NM	NB	NM	NM	NM	Z	PS	PM
NS	NB	NM	NM	NS	Z	PM	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NB	NM	Z	PS	PM	PB	PB
PM	NM	NS	Z	PM	PB	PB	PB
PB	NS	Z	PS	PM	PB	PB	PB

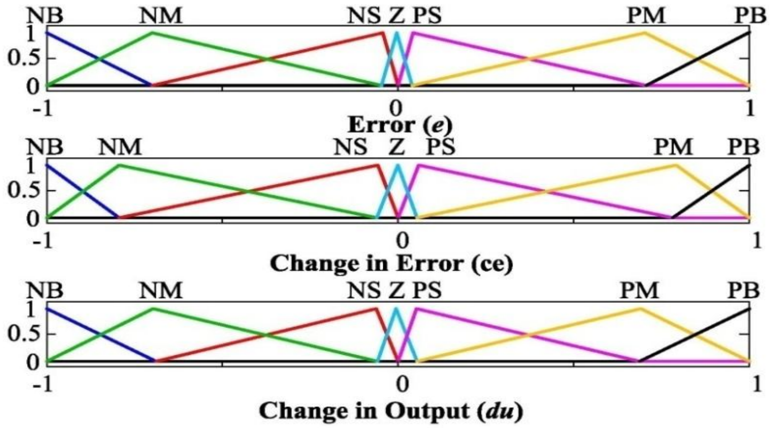

Fig. 8 Optimized input and Output Membership Functions of Fuzzy Controller

VI. SIMULATION RESULTS AND DISCUSSION

Fig. 9 shows the step Reponses of Luo converter with FLC and PSO-FLC. In the present case, the input voltage step is varied from 10 to 12.5 V at 0.02 sec and from 12.5 V to 10 V at 0.04 sec. The time response of the output voltage in a closed-loop system compensated by a PSO fuzzy controller is illustrated in Fig. 10. The changes in the input voltage do not take any variations in the output voltage since the controller adopt the variations in the parameters and continuously track the reference voltage and therefore, the duty cycle of the MOSFET is changed so as to maintain the output voltage. This proves the effectiveness and the robustness of the controller. Table IV list out the circuit parameter of POELC.

Fig. 10 shows the output voltage of the converter with fuzzy controller and PSO-FLC subject to the step change of the line voltage. When the input voltage is increased suddenly from 10 V to 12.5 V, it is observed that the settling time is 9.9 msec and peak overshoot is 29 % for Fuzzy controller and for PSO-FLC the settling time is 3.28 msec and peak overshoot is 20%. When the input voltage is changed from 12.5 V – 10 V, the settling time is 9.7 msec and the peak overshoot is 28.6% for FLC and the settling time is 3.4 msec and the peak overshoot 19.5% for PSO tuned FLC.

Fig. 11 shows the dynamic behaviour of the converter system with a ± 20% step-change in load resistance. The PSO tuned controller takes 3.66 msec settling time with an overshoot of 11.9% as compared to 10 msec and 17.7% in case of FLC tuned controller when the load changes from 10 to 12Ω. The PSO tuned controller takes 3.8 msec settling time with an overshoot of 11.5% whereas FLC takes 9.75 msec and 18% when the load decreases from 12Ω to 10Ω.

The simulation is carried out by varying the system reference voltage where the result for the output voltage is shown in Fig 12. The reference voltage is changed from 20 V to 30 V at moment t = 0.02 sec where it can be seen that the corresponding output voltage has been changed to 30V. Here, the controller adopts the change in reference value, vary the duty cycle of the converter accordingly and produce the reference as the output voltage, the controller approximately does not take any time to vary the output voltage from 20V to 30V

TABLE IVV CIRCUIT PARAMETERS FOR NOELC

Parameters	Values
Inductors (L_1& L_2)	100 µH
Capacitors (C & C_0)	5 µF
Load resistance (R)	10Ω
Input Voltage (V_I)	10V
Output Voltage (V_O)	-20V
Switching frequency (f_s)	50KHz
Range of duty ratio (*d*)	0.1-0.9
MOSFET	IRF250N
Diode	UF5042

Table V shows the performance evaluation of Luo converter in terms of percentage overshoot, rise time and setting time under startup, set point change, change in the input and load.

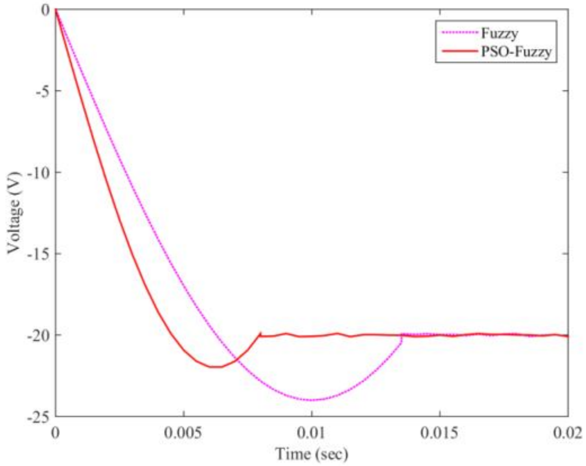

Fig. 9 Step Responses of Luo Converter with FLC and PSO-FLC

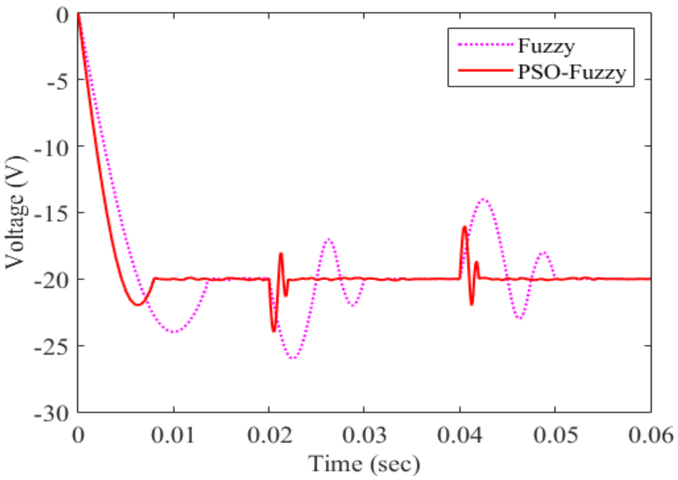

Fig. 10 Closed Loop Responses under ± 25% Line Disturbances

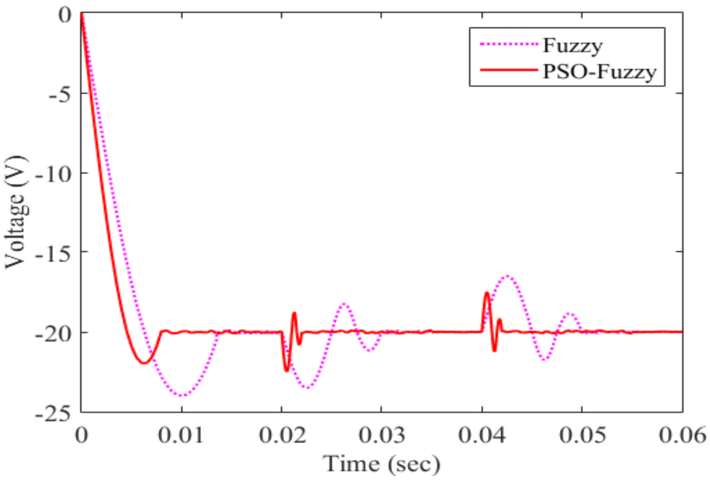

Fig. 11 Closed Loop responses under ± 20% Load Disturbances

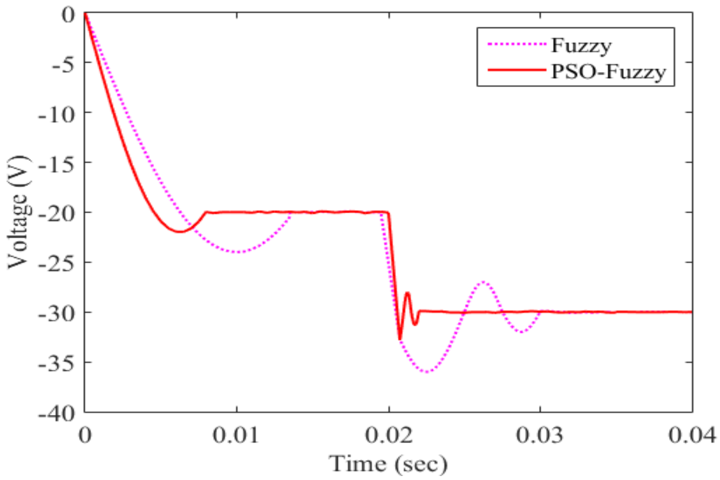

Fig. 12 Servo Responses of Luo Converter

TABLE V

PERFORMANCE COMPARISON OF PSO-FUZZY AND FUZZY CONTROLLERS

		Parameters	Fuzzy	PSO-Fuzzy
Start up Transient		Rise time (msec.)	6.2	4.5
		Settling time (msec.)	13	7.7
		% Peak overshoot	19	10.4
Line Disturbance	25%Supply Increase at 0.02 sec	Settling time (msec.)	9.9	3.28
		% Peak overshoot	29	20
	25% Supply Decrease at 0.04 sec	Settling time (msec.)	9.7	3.4
		% Peak overshoot	28.6	19.5
Load Disturbance	20% Load Increase at 0.02 sec	Settling time (msec.)	10	3.66
		% Peak overshoot	17.7	11.9
	20% Load Decrease at 0.04 sec	Settling time (msec.)	9.75	3.8
		% Peak overshoot	18	11.5
Servo response	50% set point change at 0.02 sec	Settling time (msec.)	9.2	1.4
		% Peak overshoot	20	8

VII. CONCLUSIONS

In this work, Luo converter with fuzzy control system has been modelled and optimized using PSO algorithm. Comparative studies were made with the two proposed controllers for a sudden change in input voltage and load change. The PSO-fuzzy controller gives the better performance and was more robust for disturbances in comparison with the fuzzy controller. Simulated results obtained validate the effectiveness of the proposed PSO-fuzzy control strategy and the controlled converter behaves very well with very less overshoot and settling time. PSO method is an efficient global optimizer for continuous variable problems and it is easily implemented with few parameters to be tuned.

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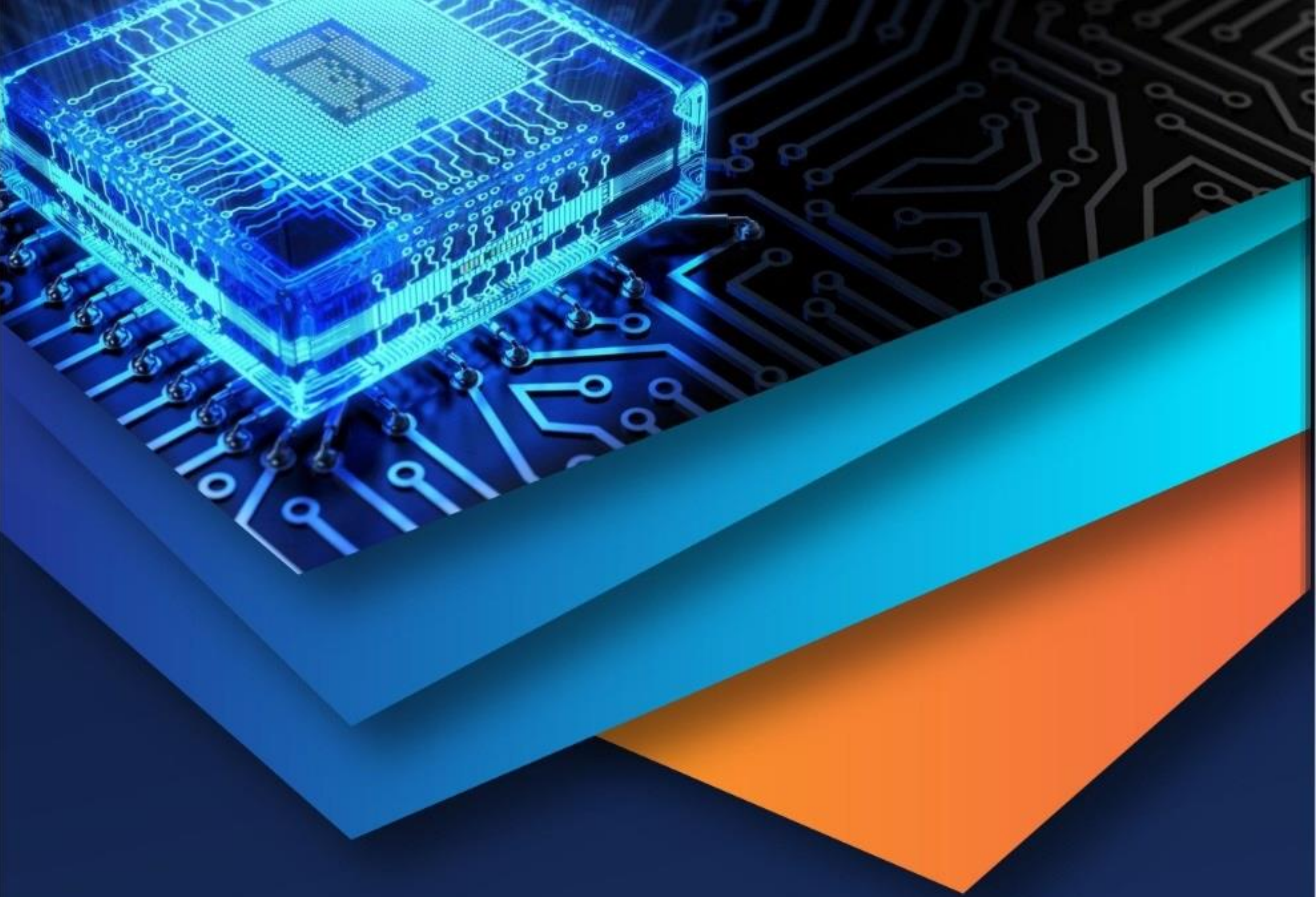

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