A Nature Inspired Optimization Based Fuzzy Logic Controller for Grid Connected Photovoltaic Inverter

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Abstract- *In this study, a novel Fuzzy Logic Controller (FLC) based on Firefly Algorithm (FA) is presented for a grid connected photovoltaic (PV) inverter. The FA is used to obtain the membership functions for the FLC. This technique evades the conventional trial and error procedure for obtaining membership functions of FLC. The fuzzy logic based current and voltage control schemes generate the pulses for three phase inverter based on sinusoidal pulse width modulation. The system shows stable ac output voltage with grid and load disturbances during the transient and steady state operation. With the results 4.99% and 2.71% of total harmonic distortion of current and voltage respectively proves that presented control system is having good performance. The efficacy of the system and control algorithm is verified in the MATLAB/SIMULINK.*

Keywords- Fuzzy Logic Controller, Three Phase Photovoltaic Inverter, Total Harmonic Distortion, Firefly Algorithm, Incremental Conductance MPPT

I. INTRODUCTION

The total energy consumption of the world is growing at a rate of 2% every year. The rise in prices of conventional energy sources and their negative impact on environment have resulted in the need of renewable energy. Among the environment friendly energy sources available, the solar Photo Voltaic (PV) energy is having vast potential and scope due to its abundance and accessibility. In addition, the PV source has become an important source of electrical energy in remote areas.

The PV power system ranges from few kW to MW. However it can produce only Direct Current (DC) power. So a power inverter is essential to convert it to ac power, which can be used to feed ac loads or can be exported to utility grid [1]. The successful implementation of PV system depends on proper control techniques of the inverter [2]. Various control issues of the inverter that have been focused by the researchers are nonlinearity behaviour, self-consumption losses [3], output fluctuation, harmonics distortion level [4], electromagnetic interference, weather dependence and low efficiency of PV [5], potentiality to work at high frequency and speed for pulse width modulation (PWM) signal generation, attainment of unity power factor, and dc bus voltage fluctuations [6]. So it is very important to design an inverter controller to improve the PV system performance [7].

Researchers used Proportional – Integral (PI), and PI-Derivative (PID) controllers to control the inverter [8]. However, the drawbacks of PI, PID controllers such as discretization of grid frequency, large output filter and absence of intelligence level encouraged the researchers to use the controllers based on artificial intelligence such as fuzzy logic [9], neural network [10], neuro fuzzy [11], genetic algorithm, etc.

Fuzzy Logic Controller (FLC) is the simplest among the different intelligent controllers because of its adaptability to complex systems without a mathematical model. The FLC is superior in terms of response time, robustness, settling time and insensitivity to load and parameter variation. So the FLC has become popular in the design of controllers for three phase inverter. However, the performance of FLCs depends on Membership Functions (MFs), number of rules and rule basis. All these elements are obtained manually by a trial and error procedure which is so tedious and time immersing.In existing method available in literature [12],Particle Swarm Optimization (PSO) was used to optimize the FLC for Maximum Power Point Tracking (MPPT) in grid connected photovoltaic inverter system. But PSO algorithm is prone to premature convergence and selection of proper optimization technique is crucial.

In the present study, FLC optimization for three phase inverter in a grid connected PV system is obtained using firefly algorithm (FA). FA is a nature inspired metaheuristic optimization algorithm motivated by the flashing actions of fireflies and advised for the multimodal problems. So this algorithm is used to optimize the MFs for the FLC.The optimization is done by minimizing the Mean Square Error (MSE) of the output voltage of three phase photovoltaic inverter, which is the objective function in the present study. The system is designed in MATLAB environment to assess the performance of the presented controller under wavering load conditions and transients of grid connection.

II. SYSTEM DESCREPTION

The block diagram of PV system with three phase inverter connected to utility grid considered in this paper is illustrated in Figure 1. It consists of PV modules, DC-DC converter, FLC system, three phase inverter, loads and utility grid. The control system embeds the sub control blocks like voltage and current control functions, PWM signals.

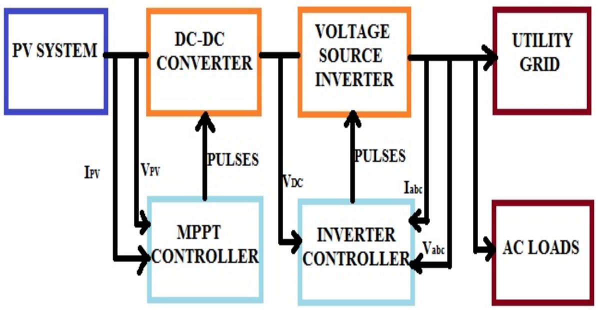


Figure 1. Block diagram of grid connected PV system

For simplification, the PV system in this paper is executed with a fixed solar insolation and temperature. The parameters of the PV system considered in this paper are listed in the Table1.

Table 1.PV System Parameters

PV system parameter	**Value**
Module open circuit voltage, V_{OC}	44.5 V
Module short circuit current, I_{SC}	8.2 A
Voltage at maximum power, V_{mp}	35 V
Current at maximum power, I_{mp}	7.71 A
No. of modules in an array, N_S	11
No. of arrays in the system, N_P	2
Output voltage of the system, V_{PV}	385 V
PV system power capacity, P_{PV}	5.8kW
Solar irradiation, G	1000 W/m^2
Temperature, T	25^{0}C

The voltage and current relations for single diode model PV array can be given as\

$$I = I_L - I_0\left[e^{\frac{q}{AKT_c}(V+IR_s)}\right] \quad (1)$$

The voltage and current produced by the PV system depends on the combination of N_S (number of series modules) and N_P (number of parallel arrays). The output power of the PV system is given as

$$P_{PV} = I_{PV} \times V_{PV} \quad (2)$$

The Incremental Conductance (IC) based MPPT algorithm [13] is used to generate suitable pulses for the dc-dc converter to get maximum power output from the PV system. In the IC method, the controller senses the incremental variation in the PV voltage and current to find out the effect of change in voltage. This method uses the incremental conductance (dI/dV) of the PV array, to calculate the sign of the change in power which in turn varies the duty cycle of the dc-dc converter.

The PV system voltage V_{PV} is boosted to 700V by the dc-dc converter for the inverter dc input voltage, V_{dc}. This is obtained by changing the duty cycle, D of the power switch using the PWM method, as explained in Equation (3).

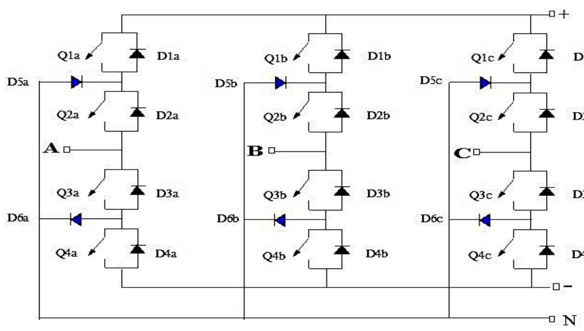
$$V_{dc} = \frac{V_{PV}}{1-D} \quad (3)$$

The DC power is converted into AC power using Neutral Point Clamped (NPC) three level inverter. The Figure 2(a) presents the configuration of NPC inverter [14]. It is a 3-level 3-phase Voltage Source Converter (VSC). The VSC converts the 700V DC link voltage to 415V AC and keeps unity power factor. The DC link with two capacitors each of 60µF links the dc power obtained from boost converter to the inverter system and also stabilizes the input voltage of the inverter. A filter inductor of 1.8 mH is used to connect the system to ac loads and utility grid. It reduces the high frequency harmonic components injected to the grid. The Sinusoidal PWM signals for the inverter switches are produced by the controller based on the V_{dc} voltage, inverter output voltage, current and strategy of control algorithm used.

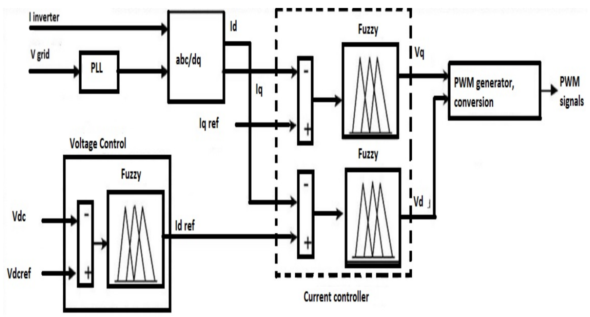
III. INVERTER CONTROL STRATEGY

The functional components present in the inverter controller are phase locked loop for synchronizing the system to grid, abc-dq_0 transformation, current and voltage regulators, FLCs, PWM signal generation and signal conversion. The configuration of the inverter controller is presented in Figure 2(b). The inverter control system works in two modes of operation namely stand alone and grid connected [15].

To ease the three phase analysis and design of the controller the inverter voltage is sensed and converted into dq_0 components using park's transformation [16]. The FLC stabilize the output frequency and voltage in both transient and steady state condition using the reference voltage. After synchronization the system is connected to the grid and it operates in the grid connected mode.



(a)



(b)

Figure 2.(a) Three Phase NPC Inverter configuration (b) Block Diagram of inverter controller.

During the grid connected mode, the current is controlled by the controller. The desired current is tracked by the FLC based on the error, E generated between the real current components I_d and I_q and the reference current components I_{dref} and I_{qref} respectively. In the voltage control scheme the dc link voltage V_{dc} is compared with reference voltage, V_{dref} and error is produced. The FLC is used for the minimizing the error produced. The output signal obtained from the controller is the I_{dref} current which is used in the current control scheme.

To find out V_d and V_q the Error, E and the Change of Error, CE which is obtained by taking the derivative of the error, E are then used as the inputs for FLC at each sampling time. The V_d and V_q obtained now are again changed into the reference frame voltages V_a, V_b, and V_c using inverse park's transformation [16].

IV. DESIGN PROCEDURE OF FUZZY LOGIC CONTROLLER

As the process of conversion of power from dc to ac using PV inverter is nonlinear, fuzzy logic control is a proper method to use in the control system of PV inverter. The FLC architecture is depicted in Figure 3.

There are four steps followed in the design of FLC.

4.1 Defining the module characteristic: The first step is important to find out the fuzzy location and for the selection of number of inputs and outputs. In this study, the FLC controls the PV inverter, so E and CE are considered as inputs and the missing variable V_d (or V_q) is considered as output.

4.2 Fuzzification: In this step, the inputs are decomposed into suitable linguistic values, such as "*small*" or "*big*". The trapezoidal and triangular MFs are used here.The process of Fuzzification converts E and CE into fuzzy set by using MF degrees $\mu_e(E)$ and $\mu_e(CE)$, which range from 0 to 1. In the standard FLC design, a trial and error method is used for selecting number of MFs and adjusting the boundary values of each MF until satisfactory result is obtained. However, this process is laborious and time perishing. So in this paper Firefly Algorithm is used to obtain the MFs explained in next section. The inputs are subjected to an inference engine after the fuzzification to generate fuzzy output.

4.3 Inference engine design: In this step, decision is made as per the information provided in knowledge base, which consists of linguistic labels and control rules. There are two inferencing systems in fuzzy logic, namely Mamdani type and Sugeno type. Due to simple implementation steps of Mamdani type inferencing system, it is used in this paper.

4.4 Defuzzification: The selection of Defuzzification method is the final step. A crisp value is generated in this step. The most common methods are Mean of Maximum (MoM) and Centre of Area (CoA). The CoA method is widely used because it is more accurate than MoM method and it generates the centre of gravity of the MFs.

V. PROPOSED FUZZY LOGIC CONTROLLER DESIGN PROCEDURE

This paper presents a method to optimize the MFs of FLC using Firefly Algorithm (FA) which is a metaheuristic optimization algorithm. The metaheuristic optimization algorithms are used for solving incomplete, complex and multimodal problems [17] which are difficult to solve by using classical methods. A set of solutions which are huge to be completely sampled are sampled by Metaheuristics. The design process of FLC based on FA is presented in Figure 4.

5.1 Overview of Firefly Algorithm*:*The FA is effective in multimodal optimization solution.The concept behind the FA is all fireflies are unisex. There will not be any male and female. So, one firefly attracts other fireflies irrespective of their sex. Attractiveness of the fireflies depends on their brightness. Thus, for any two flashing fireflies, the less bright firefly will move towards the brighter firefly. As the attractiveness is proportional to their brightness and it increases as their distance decreases and vice versa. If no other firefly is brighter than the particular firefly, it will move randomly. The brightness of a fireflyis determined by the landscape of the objective function. The brightness is proportional to the value of the given objective function, for a maximization problem. Other form of brightness is outlined similar to the fitness function of genetic algorithms.

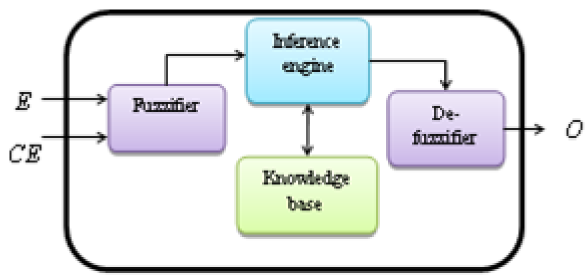


Figure 3. FLC Architecture

5.2 Problem Formulation: There are three basic components that are important for all the optimization methods. They are input vectors, objective function formulation, and optimization boundaries. These are developed and clarified to get the optimal MFs. Based on the given objective function the optimal solution is obtained by the optimization algorithm by modifying the input vector subject to the iterative process limitations.

5.2.1 Input Vector: The quantity of MFs is to be defined to deliver the solution from the optimization algorithm. Based on the quantity of MFs, the input vector Z is given by the equation (4)

$$Z_{i,j} = \left[X_{i,j}^{1} X_{i,j}^{2} \cdots X_{i,j}^{n}\right] \quad (4)$$

where,$Z_{i,j}$denotes the jth solution in the population during the ith iteration, $X_{i,j}^{k}$ is kth element of $Z_{i,j}$, and n is the total number of parameters.

5.2.2 Objective function: To evaluate the performance of input vector $Z_{i,j}$for the MFs an objective function is essential. Thus, to find the optimal values, the objective function is formulated such that $Z_{i,j}$

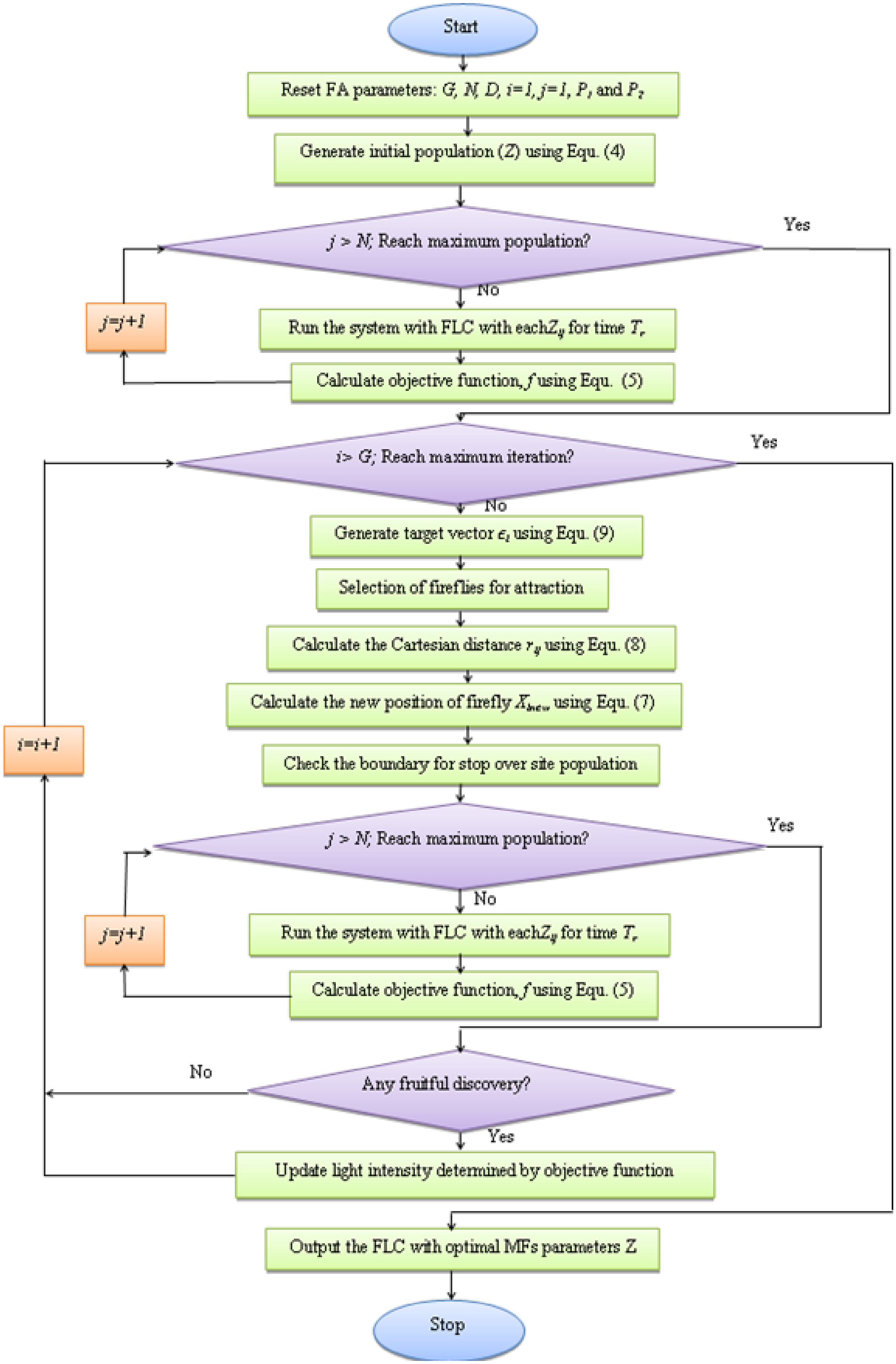


Figure 4. FLC MFs Design Procedure using FA

produces the best fuzzy control action as crisp value based on the defuzzification process. At the t^{th} sampling step in the FLC design, E and CE corresponding to V_d indicate the goodness of the crisp value of the fuzzy control action. Thus the Mean Square Error (MSE) detailed in Equation (5) attained from the measured values of V_d and the reference values V_{dref} is used as the objective function.

$$MSE = \frac{\sum_{i=1}^{l}\left(V_{dref} - V_d\right)^2}{l} \qquad (5)$$

where, l is the number of samples used to evaluate MSE, V_d is the measured value and V_{dref} is the reference value that is equal to (1 p.u.). For the optimization process, Equation (5) needs to be minimized.

5.2.3 Optimization Constraint:All the constraints of the optimization algorithm must be satisfied to find the optimal values of MF parameters. There should not be any overlap between the MF parameters. Therefore, the MF parameters should fulfil the following restriction as in Equation (6).

$$X_{i,j}^{k-1} < X_{i,j}^{k} < X_{i,j}^{k+1} \qquad (6)$$

5.2.4 Implementation Steps of FA for the Optimal FLC design: The first step of implementation of FA starts from rearranging the FA parameters namely population size (N), number of iterations (G), problem dimension (D), and control parameters (P_1 and P_2). Using Equation (4), the initial populations for MFs are produced and encrypted. Then the objective function is evaluated using Equation (5). Aappropriate running time T_r is required to populate the FLC output for the assessment of MSE in population N. After evaluation of initial population, the new position of each FLC parameter in $Z_{i,j}$ is attained using the Equation (7).

$$x_{inew} = x_i + \beta_0 e^{-\gamma r_{ij}^2}\left(x_j - x_i\right) + \alpha\epsilon_i \qquad (7)$$

In Equation (7), the Cartesian distance r_{ij} is determined using Equation (8).

$$r_{ij} = \left\|x_i - x_j\right\| = \sqrt{\sum_{k=1}^{d}\left(x_{i,k} - x_{j,k}\right)^2} \qquad (8)$$

And $\epsilon_i$is a vector of random numbers drawn from a Gaussian distribution or uniform distribution given by

$$\epsilon_i = rand - \frac{1}{2} \qquad (9)$$

where, *rand* is random number generator uniformly distributed in [0,1]. The objective function is analysed again after updating the values of $Z_{i,j}$ in the population. Until the maximum iteration count is reached, the process of position updating and objective function re-evaluation is repeated.

VI. DESIGN OF FUZZY LOGIC CONTROLLER USING THE PROPOSED METHOD

A PV inverter system with specifications 5.8kW, 415V, 50Hz is modelled in MATLAB/Simulink environment (Figure5(a)) with three loads to present the application of an optimum FLC design. The three phase output voltages (V_a, V_b, and V_c) are measured and transformed to V_d and V_q at each sampling time t =1μs. As shown in Figure5(b), **t**he controller block consists of two FLCs that correspond to V_d and V_q in d-q reference frame. The *E* and *CE* generate new V_d and V_q and then they are converted to V_a, V_b, and V_c. the converted signals V_a, V_b, and V_c are used to generate Sinusoidal PWM signals for the inverter [18].

In each input of the FLC seven MFs defined as triangular and trapezoidal are illustrated in Figure 6. First input *E* is defined from $X_{i,j}^{1}$to $X_{i,j}^{7}$ and second input *CE* is defined from $X_{i,j}^{8}$to $X_{i,j}^{14}$. Thus each FLC input *Z* contains 14 parameters. The Table II with 49 rules presents the control rule for the FLC.

Now the input vector and control rules are outlined. With the running time of simulationt = 0.25s the optimization process explained in previous section is performed.

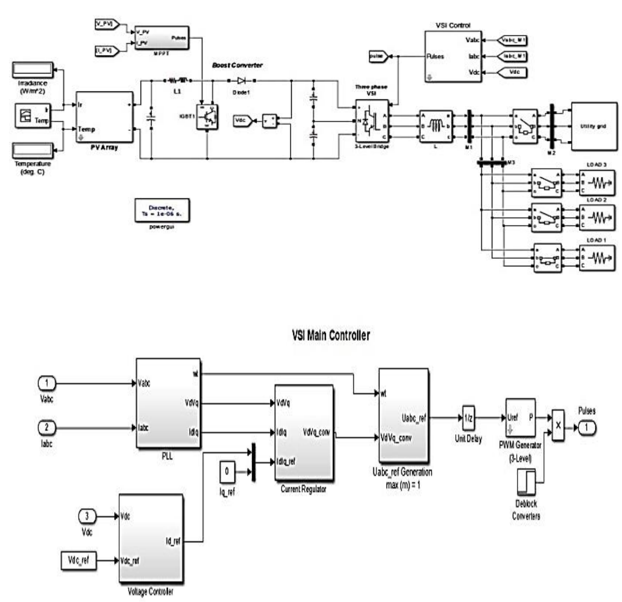


Figure 3.Simulation model of (a) Grid Connected Three Phase PV System (b) Inverter Controller

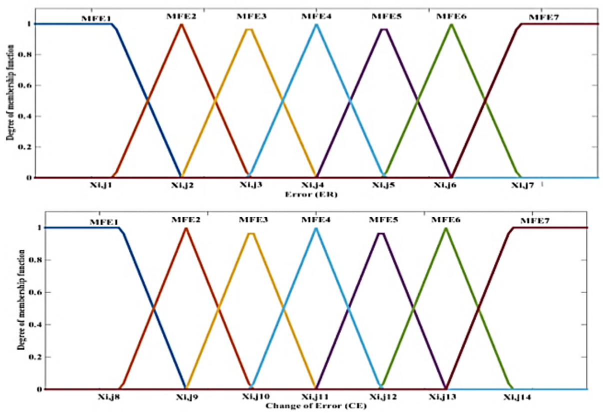


Figure 4.FLC with 7 MFs for (a) E and (b)CE

For the initialization of FA based optimization process, the parameters considered are as follows. The dimension of the problem (D) is 14, number of populations (N) is 20, the number of iterations (G) is 100, and the control parameters P_1 and P_2 are 0.25*rand. The FA updates the population and initiates a new iteration after creating the initial population and calculating the corresponding objective function for each vector in the input population. If FA touches maximum iteration, the FLC with the best MFs is achieved (Figure4). The new MFs of *E, CE,* and output of the FLC based on FA are presented in Figure 7.

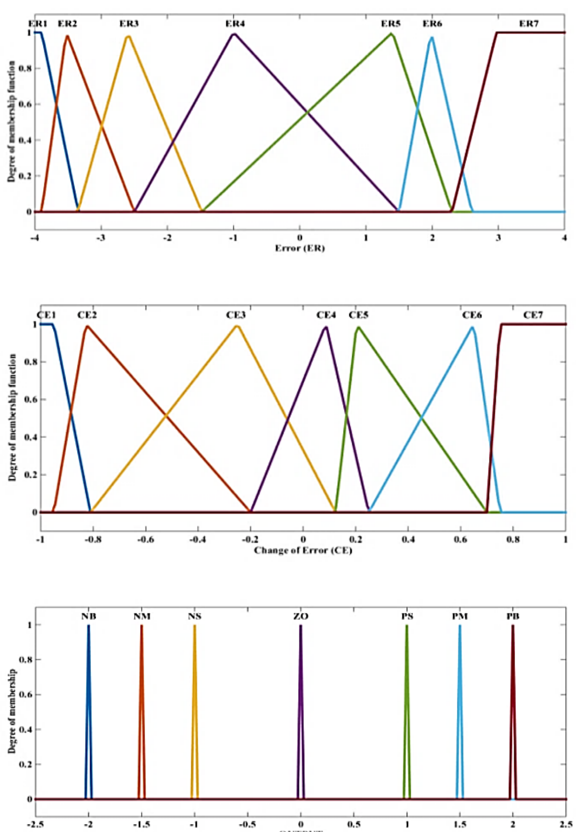


Figure 5. MF of the (a) E, (b) CE and (c) Output

Table 2.Fuzzy Control Rules Based on Seven MFs

Error (E)	Change of Error (CE)						
	$MFCE_1$	$MFCE_2$	$MFCE_3$	$MFCE_4$	$MFCE_5$	$MFCE_6$	$MFCE_7$
MFE_1	NB	NB	NB	NB	NM	NS	ZE
MFE_2	NB	NB	NB	NM	NS	ZE	PS
MFE_3	NB	NB	NM	NS	ZE	PS	PM
MFE_4	NB	NM	NS	ZE	PS	PM	PB
MFE_5	NM	NS	ZE	PS	PM	PB	PB
MFE_6	NS	ZE	PS	PM	PB	PB	PB
MFE_7	ZE	PS	PM	PB	PB	PB	PB

VII. SIMULATION AND RESULTS

The PV inverter system connected to grid as shown in Figure 5 is developed in MATLAB/Simulink environment to validate the proposed FA based FLC system under grid and load variations. The system is simulated for a period of t=0.25 seconds with sampling time of 1μs. For observing the response of the PV inverter, theload on the system is varied.

In the first phase from 0 to 0.1s the load on system is 5.8 kW which is equal to the power generated by PV system. In this phase the system is started in standalone mode. The inverter voltage and current waveforms are presented in figure 8. Once the system is stabilized then the system is connected to grid. The grid voltage waveform presented in figure 9 shows the sinusoidal waveforms of 50 Hz have voltage of 1 p.u., which is equivalent to the rms line voltage of 415 V or phase voltage of 240 V.

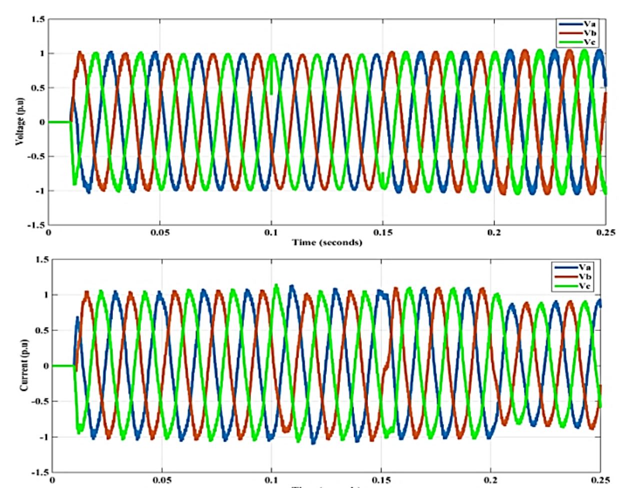


Figure 6. Inverter (a)Voltage (b)Current

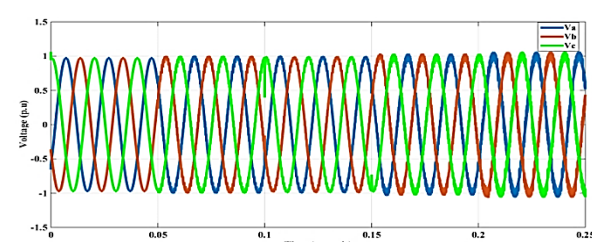


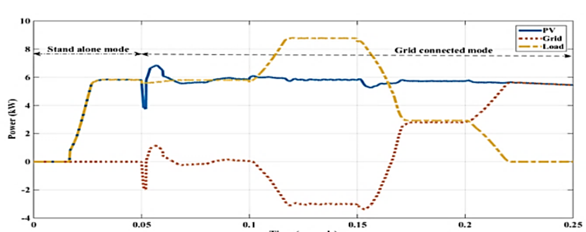
Figure 7. Grid Voltage

The system is connected to the grid at 0.05s. A small step transient condition is observed in the system power flow when switching the inverter from standalone mode to the grid connected mode as shown in the figure 10 (a). The Figure 10 (a) shows the system power flow when a manually tuned FLC is used for the inverter [15]. However, the developed FA based FLC controller compensates the overall transient effects as shown in the figure 10 (b). Also the time taken by the developed system to come down to steady state condition is 0.015s which is very low compared to the manually tuned FLC system where it takes 0.03s to reach steady state condition.

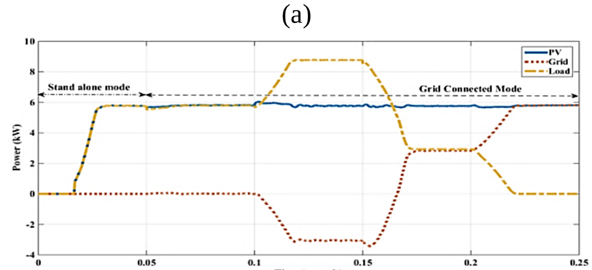
In the second phase from 0.1s to 0.15s the load on the system is increased to 8.8 kW which is approximately 150% of the power generated by the PV system. The additional power required by the load is taken from the grid. The effect of increase in load is very low on the developed FA based system than the manually tuned FLC based system.

In the third phase from 0.15s to 0.2s the load on the system is reduced to 3 kW, which is almost half of the power generated by the PV system. Here the power generated by the system is more than the load power required. The additional power generated by the system is exported to the grid which can be observed in the figure 10. Due to the sudden decrease in load the stability of the system is disturbed. But the proposed FA based system reaches the final steady state very quickly in 0.005s compared to the manually tuned FLC system which takes 0.015s to reach the final state.

In the fourth phase from 0.2s to 0.25s the load on the system is zero. Now the total power generated by the PV system is exported to the grid.



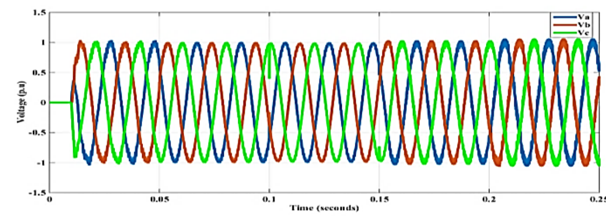
(a)



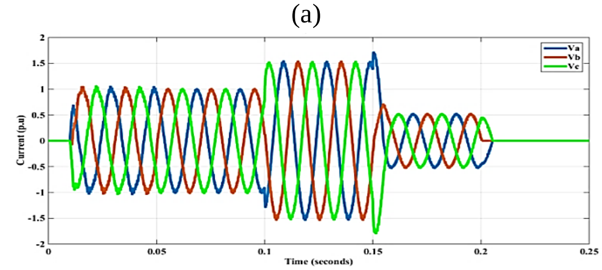
(b)

Figure 8. Inverter System Power Flow (a)FLC (b)FA based FLC

The corresponding load voltage and current waveforms during the load demand variations are shown in figure 11. The criterion of having quality output power acquiring lower voltage and current harmonic contents for the inverter is important especially when connecting the system to the grid. By using the Fast Fourier Transform (FFT) technique, the THD of the phase voltage and current waveforms are calculated to be 2.81% and 4.99%, respectively. These levels are below 5% and hence, complied with the IEEE Std. 929-2000 [19]. The waveforms and their respective harmonics spectrums are shown in figures 12(a) and 12(b).

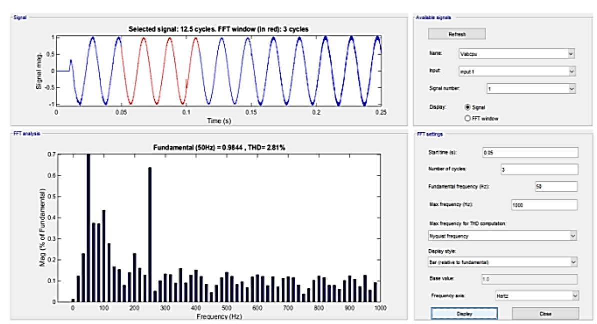


(a)

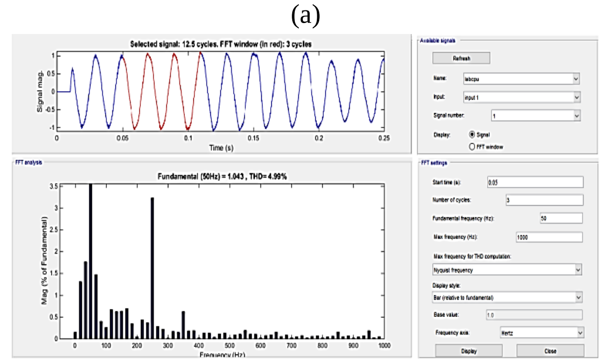


(b)

Figure 9. Load (a)Voltage (b)Current



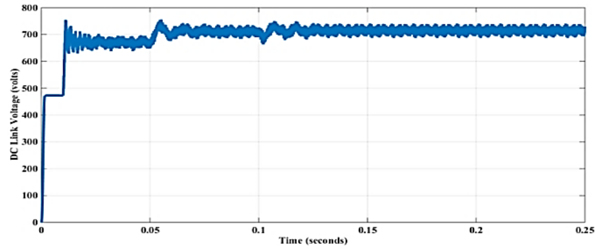
(a)



(b)

Figure 10.THD and Harmonics Spectrum of (a) Inverter Output Voltage (b) Inverter output Current

The performance of the proposed FA based FLC and manually tuned FLC are evaluated in terms of transient and steady state response in stabilizing the DC link voltage. During the stand alone mode from 0 to 0.05s the FA based FLC shown lesser ripples and oscillations than the manually tuned FLC as shown in Figure 13. The steady state response characteristic of in grid connected mode for both the controllers was considered good as can be seen after 0.05s.



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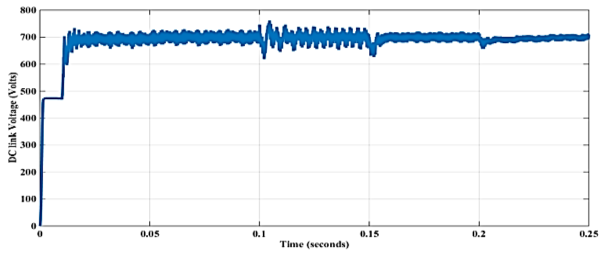

(b)

Figure 11. DC link Voltage Waveform Controlled by (a)FLC (b)FA based FLC

VIII. CONCLUSION

The modeling of FA based FLC for high performance inverter controller for a grid connected PV system has been presented in this paper. The control algorithm was verified in MATLAB/Simulink environment. First, a method has been devised to change the MF of the FLC automatically. Second, to tune the MFs of the FLC in an effective manner, a suitable objective function was developed to minimize the MSE of the output voltage of the three phase inverter. Finally, a novel optimization method known as the FA was proposed to tune the MFs of the FLC instead of trial and error procedure. The obtained results showed that the developed FA based FLC is very effective in reducing the transients produced during the grid connection time and load variations, compared to the trial and error based FLC and also in stabilizing the inverter output voltage.

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