

VHDL Based Maximum Power Point Tracking of Photovoltaic Using Fuzzy Logic Control

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ABSTRACT

It is important to have an efficient maximum power point tracking (MPPT) technique to increase the photovoltaic (PV) generation system output efficiency. This paper presents a design of MPPT techniques for PV module to increase its efficiency. Perturb and Observe method (P&O), incremental conductance method (IC), and Fuzzy logic controller (FLC) techniques are designed to be used for MPPT. Also FLC is built using MATLAB/SIMULINK and compared with the FLC toolbox existed in the MATLAB library. FLC does not need knowledge of the exact model of the system so it is easy to implement. A comparison between different techniques shows the effectiveness of the fuzzy logic controller techniques. Finally, the proposed FLC is built in very high speed integrated circuit description language (VHDL). The simulation results obtained with ISE Design Suite 14.6 software show a satisfactory performance with a good agreement compared to obtained values from MATLAB/SIMULINK. The good tracking efficiency and rapid response to environmental parameters changes are adopted by the simulation results.

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1. INTRODUCTION

At present worldwide have an energy crisis so that renewable energy is a necessary solution to conventional resources problems [1]. Photovoltaic (PV) energy is highly recommended in electrical power applications. It is crucial to operate the PV systems near the maximum power point to increase the PV system efficiency. However, the nonlinear nature of PV array depends on the array terminal operating voltage. Therefore, the tracking control of the maximum power point is a complicated problem. To overcome these problems, many conventional tracking control strategies have been proposed such as perturb and observe [2],[3], incremental conductance [4], parasitic capacitance [5], constant voltage [5], the hill climbing strategy [6]. Intelligent MPPT controller techniques, such as neural network (NN) and fuzzy logic (FL) methods, have been developed [7]-[18].

Using Fuzzy logic methods for maximum power point determination of a solar array has a good stability and a high response rate. Nowadays, fuzzy based [6],[7] researches have been published due to its good performance and high accuracy. Field programmable gate arrays (FPGAs) are digital integrated circuits that contain several millions of programmable logic blocks connected together with configurable interconnections. FPGA is used for hardware implementation for many applications especially FLC because of the required high speed and parallel processing of fuzzy logic applications [19],[20].

The paper is organized as follows. In section 2, the stand-alone PV system is presented which describes the PV system and the DC-DC boost converter mathematical modeling and design. Then, proposed

MPPT control strategies are reported in section 3 which explains the perturb and observe, incremental conductance, and fuzzy logic control approach. The simulation results and discussion are illustrated in section 4 and section 5 respectively. Finally, Section 6 contains a conclusion of this work.

2. MPPT IN STAND-ALONE PV SYSTEMS

The PV stand-alone system comprises of PV module, MPPT control unit, DC/DC converter and the required load as shown in Figure 1. The PV module under test has 75W as a maximum power, 4.4A as a maximum current and 17.7V as a maximum voltage. The DC/DC boost converter is used where the proposed system operates at 48 DC voltage. Perturbation and observation, Incremental conductance, and Fuzzy logic control method are known as MPPT algorithms for PV systems which are widely used.

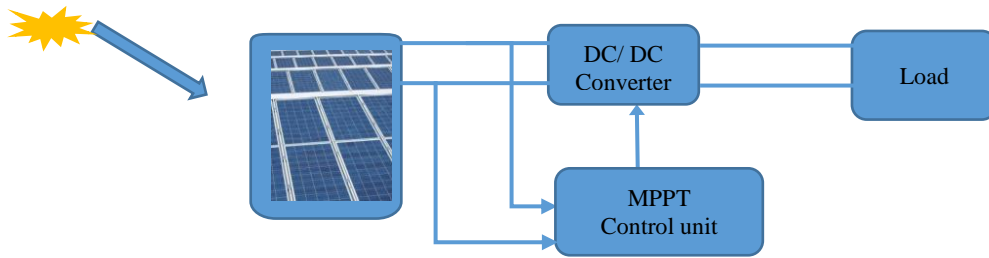


Figure 1. PV stand-alone system scheme

2.1. Photovoltaic generator model

A solar cell converts energy in the sunlight photons into electricity. PV modules consist of group of PV cells connected in series. PV modules are interconnected in a series-parallel configuration to form PV arrays. The equation that describes the I-V characteristics of PV array can be expressed as follows [21]:

$$I_{PV} = I_L - I_o \left(\exp \frac{(V + IR_s)}{V_t} - 1 \right) \quad (1)$$

where I_{PV} is the output current of PV (A), I_L is the light generated current (A), I_o is the reverse saturation current at operating temperature (A), V is the output voltage of PV (V) and V_t is the thermal voltage. The solar insolation variation effect on PV module is studied in Figure 2.

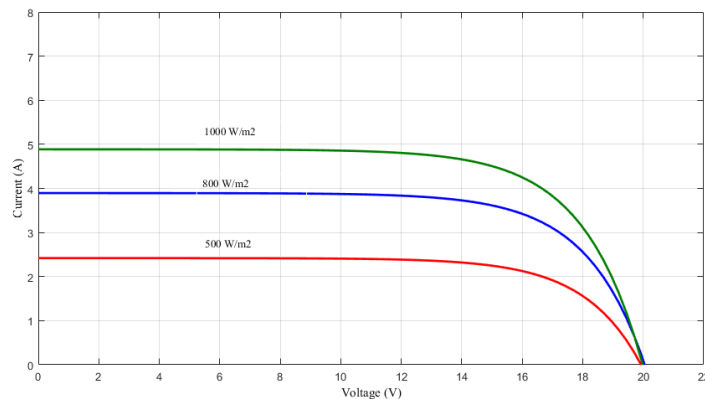


Figure 2. IV characteristic curve of PV module

2.2. Boost Converter

For PV systems, DC-DC converter is used to regulate DC voltage. The regulation is normally achieved by pulse width modulation technique using MOSFET or IGBT as a switching element. By adjusting

the PWM duty cycle, maximum power will be changed and the maximum power point is reached. The mathematical modelling of the converter in a continuous conduction mode is given by [22]:

$$\frac{V_o}{V_i} = \frac{1}{1-D} \quad (2)$$

$$L = \frac{V_i D}{f_s \text{ CRF}} \quad (3)$$

$$C = \frac{I_o D}{f_s \text{ VRF}} \quad (4)$$

where CRF is the current ripple factor, VRF is the voltage ripple factor, f_s is the switching frequency, and D is the duty cycle. By designing of proposed DC-DC boost converter under the maximum power 75W, the value of inductor and capacitor are 5 mH and 100 μF respectively.

3. MPPT CONTROL STRATEGY

There are many MPPT algorithms have been developed and implemented by researchers [2]-[18]. The MPPT algorithms used in this work are Perturb and Observe method (P&O), incremental conductance method (IC), and fuzzy logic method. These methods will be discussed below in detail.

3.1. MPPT control with perturb and observe method

The main concept of perturb and observe method is to drive the system to operate in the direction of increasing PV output power. If the output power increases, then the perturbation of the voltage is made in the same direction otherwise perturbation against the original direction should be made. Figure 3 shows the flowchart of P&O technique. The following equation describes the strategy of the P&O technique [2].

$$\text{if } \frac{dP}{dV} > 0; \quad D = D_i + dD \quad (5)$$

$$\text{if } \frac{dP}{dV} < 0; \quad D = D_i - dD \quad (6)$$

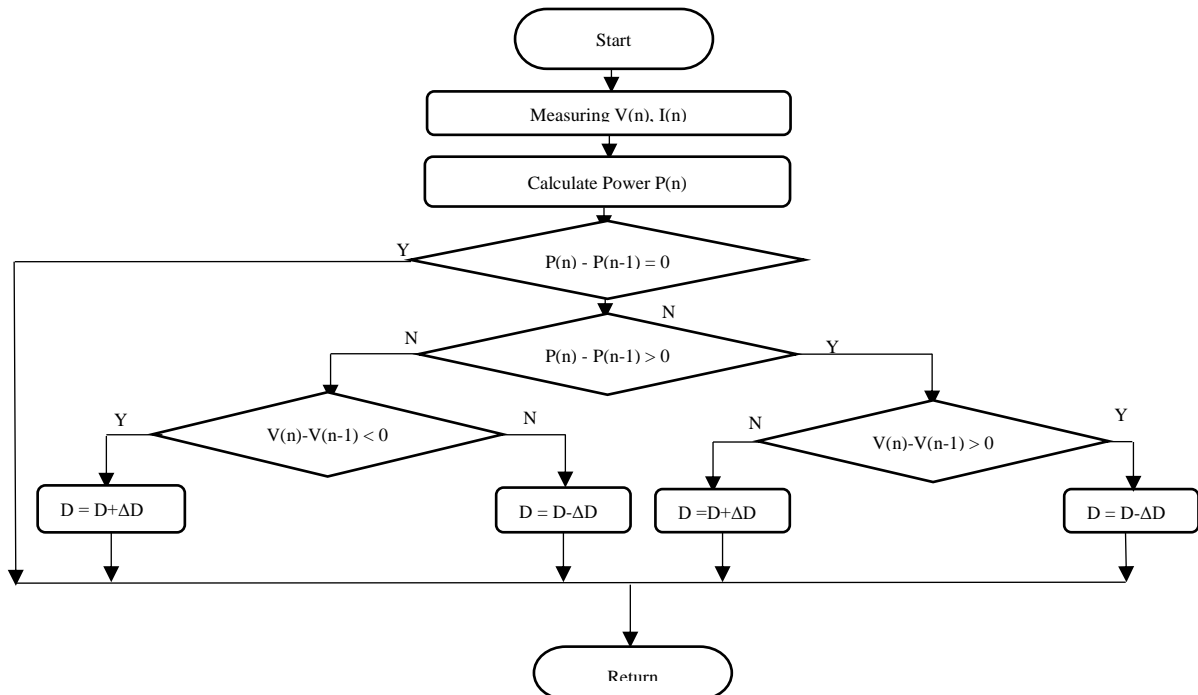


Figure 3. Flowchart of P&O algorithm

3.2. MPPT control with incremental conductance

The incremental conductance MPPT algorithm flowchart is shown in Figure 4. The incremental conductance algorithm as cleared in Eq. (7) is based on the PV power differentiation with respect to PV voltage and setting the result equal to zero as given below [4]:

$$\frac{dP}{dV} = 0; \quad \text{at MPP} \quad (7)$$

$$\frac{dI}{dV} = -\frac{I}{V}; \quad \text{at MPP} \quad (8)$$

$$\text{if } \left(\frac{dI}{dV} > -\frac{I}{V}\right); \quad D = D_i + dD \quad (9)$$

$$\text{if } \left(\frac{dI}{dV} < -\frac{I}{V}\right); \quad D = D_i - dD \quad (10)$$

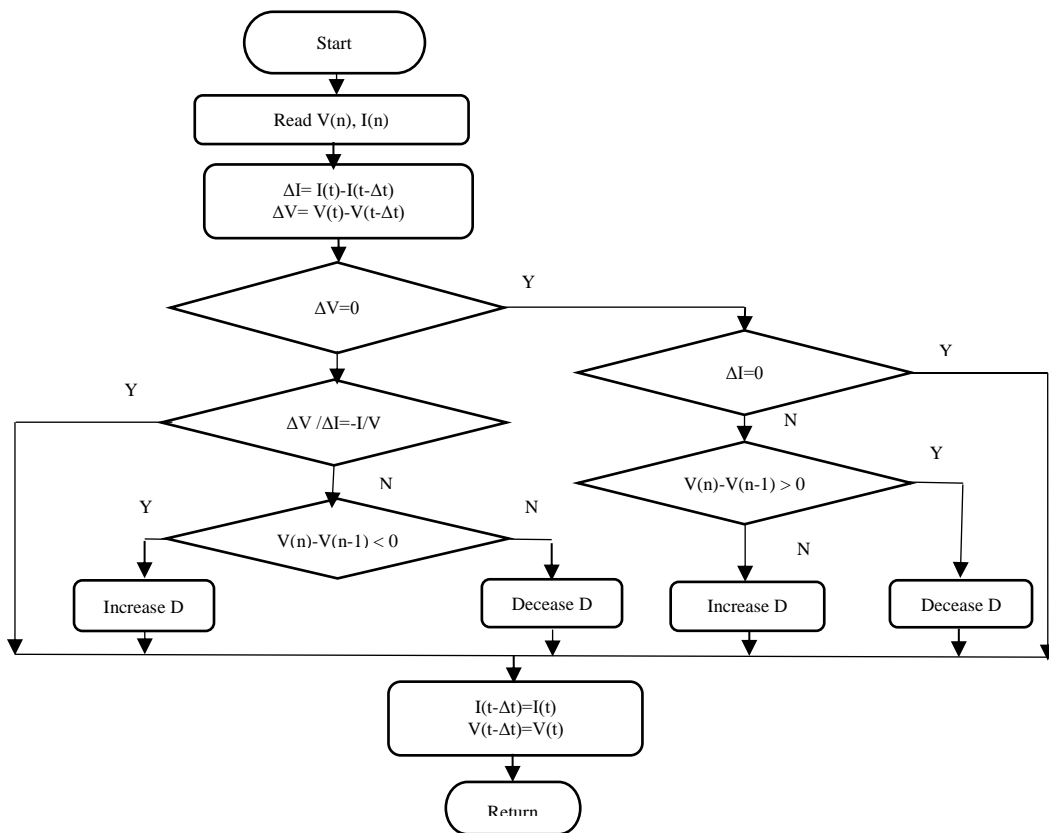


Figure 4. Flowchart of IC algorithm

3.3. MPPT control with fuzzy logic

Fuzzy logic based MPPT control contains mainly from three steps which are fuzzification, rule-base, inference and defuzzification. Two simulation methods are proposed to build FLC in MATLAB/SIMULINK. The first one focused on FLC toolbox in MATLAB library; on the other hand, the mathematical modeling of FL technique is built using MATLAB/SIMULINK. The proposed FL MPPT control has two inputs and one output. The two inputs of FLC are the error $E(k)$ and change of error $CE(k)$ as defined below [18]:

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \quad (11)$$

$$CE(k) = E(k) - E(k-1) \quad (12)$$

The FLC input variables are represented by seven fuzzy sets; Negative Large (NL), Negative Medium (NM), Negative Small (NS), zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). The rule base is presented in Table 1. Figure 5 gives the membership function of FLC input and output.

Table 1. Rule base of fuzzy logic controller

		Change of error (Ce)						
		NL	NM	NS	ZE	PS	PM	PL
Error (e)	NL	NL	NL	NL	NL	NM	NS	ZE
	NM	NL	NL	NL	NM	NS	ZE	PS
	NS	NL	NL	NM	NS	ZE	PS	PM
	ZE	NL	NM	NS	ZE	PS	PM	PL
	PS	NM	NS	ZE	PS	PM	PL	PL
	PM	NS	ZE	PS	PM	PL	PL	PL
	PL	ZE	PS	PM	PL	PL	PL	PL

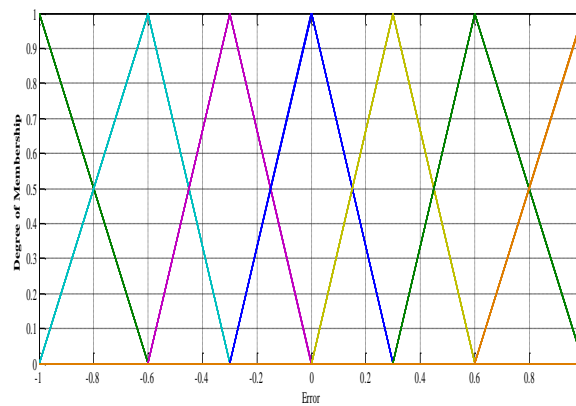


Figure 5. Membership function for fuzzy inputs and output

The mathematical modeling of triangle membership function is given by [7]:

$$\mu M(x) = \max\left(\min\left(\frac{x-x_1}{x_T-x_1}, \frac{x_2-x_1}{x_2-x_T}\right), 0\right) \quad (13)$$

The fuzzification step consists of seven membership triangle function connected together and min/max operator is used to achieve this step. Due to the seven membership triangle function there are 49 rules in total. The defuzzification step used the center of the area method. The mathematical expression of this method is shown by Eq.14 [18].

$$z = \frac{\sum_{j=1}^n \mu(z_j) \cdot z_j}{\sum_{j=1}^n \mu(z_j)} \quad (14)$$

4. SIMULATION RESULTS

In order to show the effectiveness of the MPPT, a comparison between the different control techniques has been carried out. The value of solar radiation variation levels which used for different controllers is the same. Figure 6 shows the total system design using MATLAB SIMULINK. The system consists of PV unit, P&O, IC and FLC MPPT unit using toolbox, FLC subsystem using Simulink and boost converter unit. The PV power and voltage are the input signals to MPPT unit and duty cycle is the output signal. The detailed block diagrams of control subsystem using different MPPT control technique such as P&O, IC and FLC MPPT unit using toolbox, FLC subsystem using Simulink are shown in Figure 7 to Figure 10 respectively. Figure 11 clarify the detailed model of the fuzzy subsystem. The Simulink model of triangle membership function is shown in Figure 12. The detailed simulink model of the fuzzification stage is presented in Figure 13. It consists of seven membership triangle functions connected together and min/max

operator is used to achieve the fuzzification step. Due to the seven membership tringle function there are 49 rule base in total as seen in Figure 14.

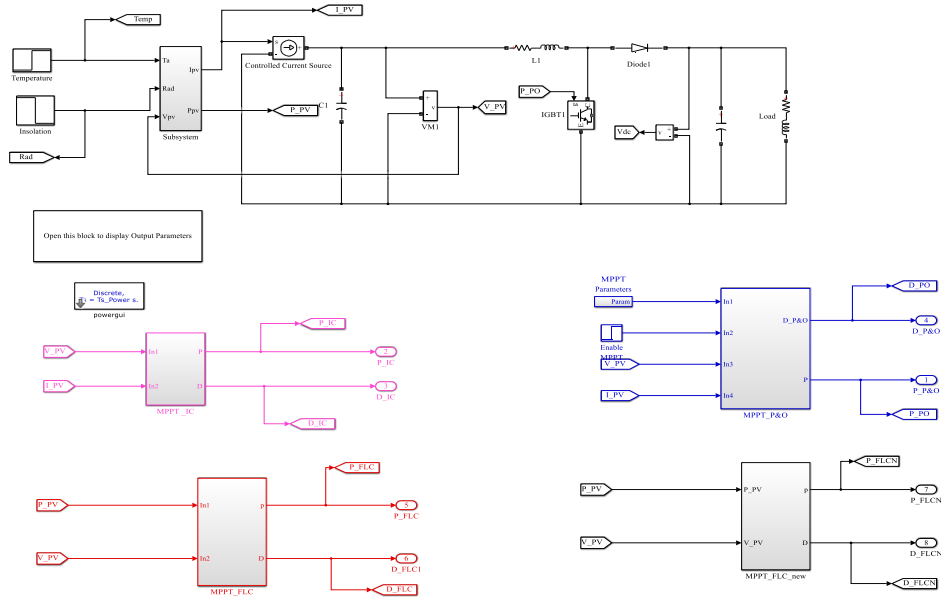


Figure 6. Total system SIMULINK

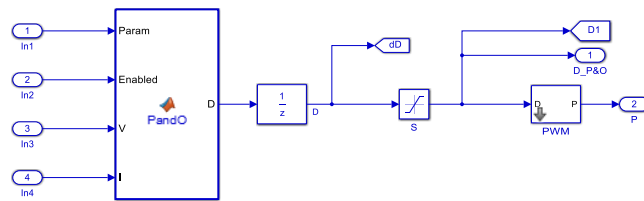


Figure 7. Control subsystem using P&O

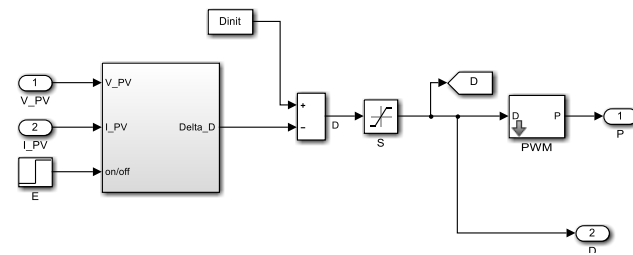


Figure 8. Control subsystem using IC

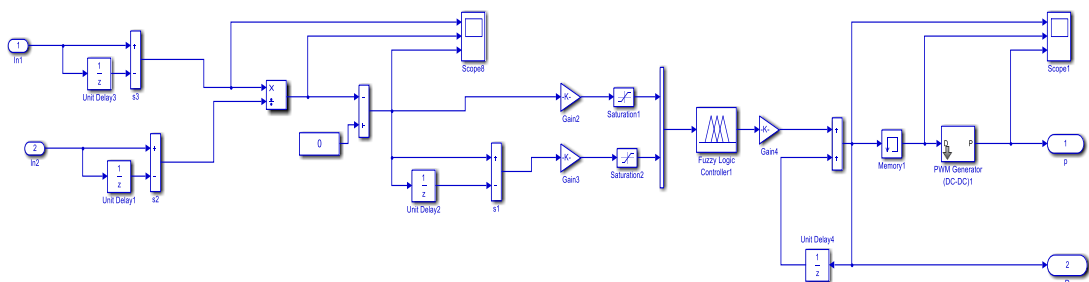


Figure 9. Control subsystem using FLC toolbox

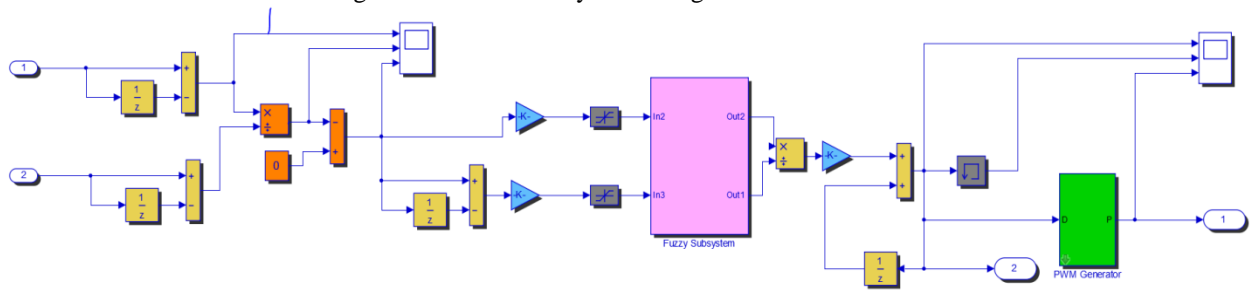


Figure 10. Control subsystem using FLC

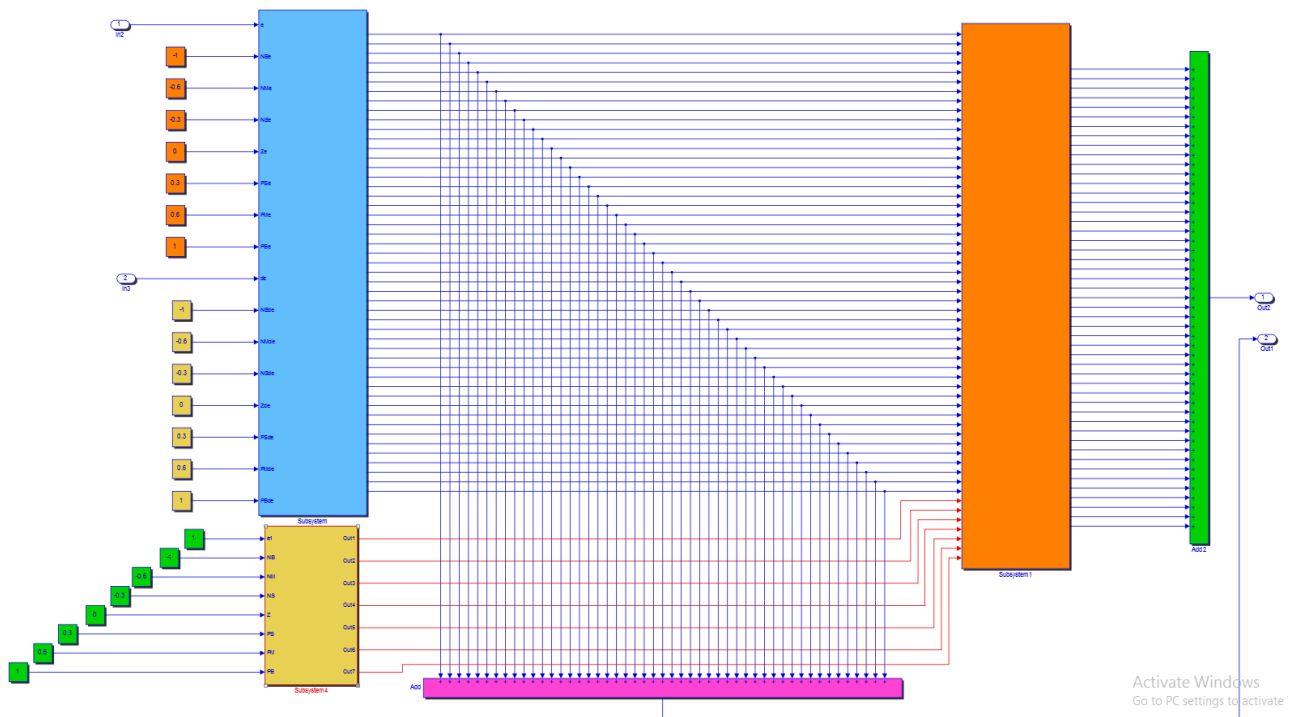


Figure 11. Fuzzy subsystem implementation in MATLAB

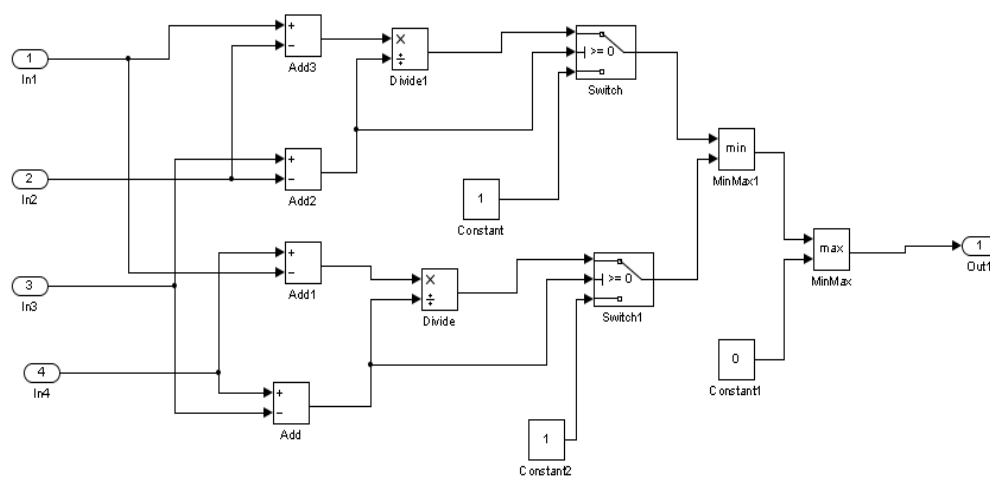


Figure 12. Tringle Membership function SIMULINK

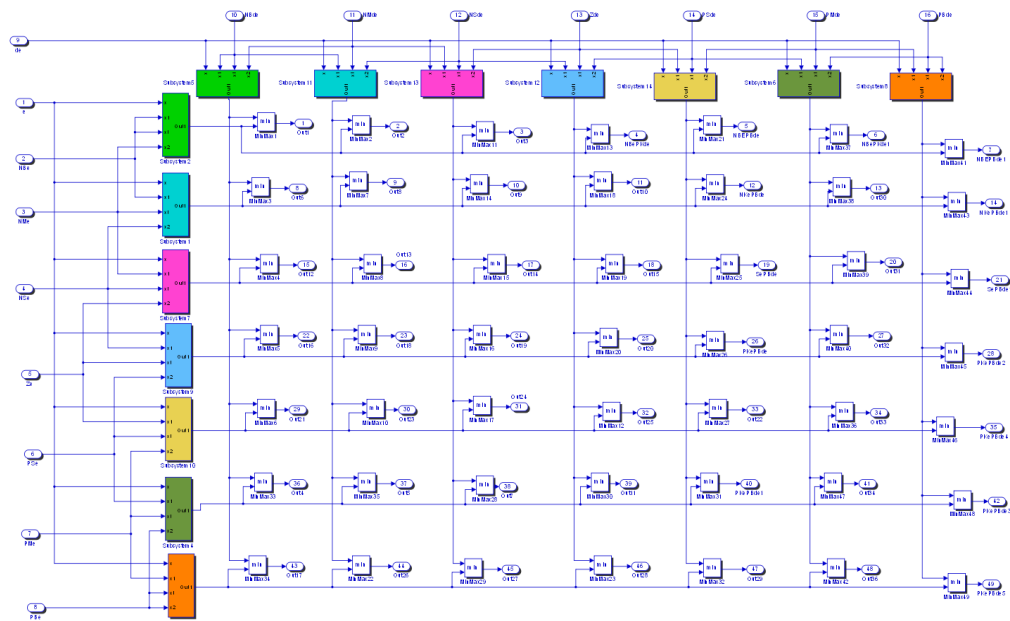


Figure 13. Fuzzification subsystem

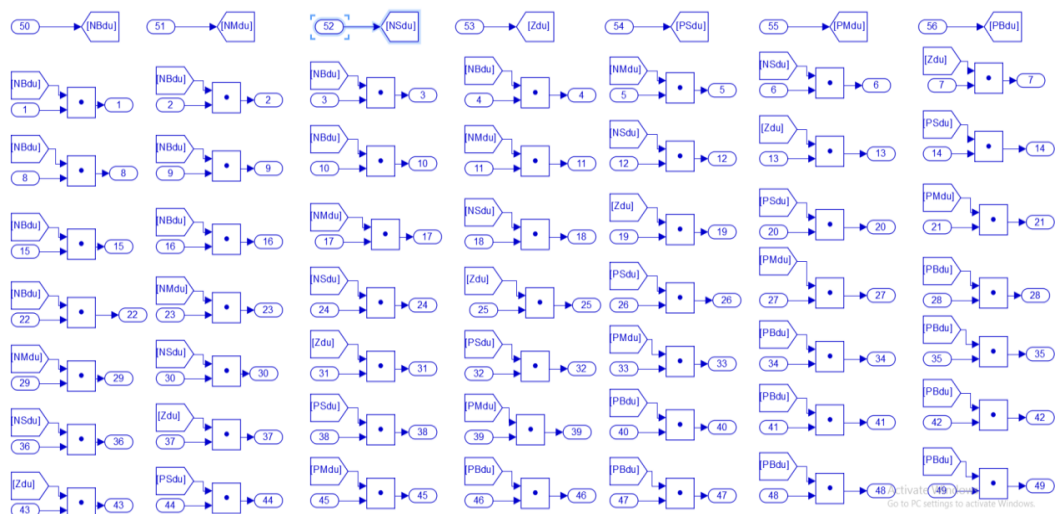


Figure 14. Rule base simulation using MATLAB

5. RESULTS AND DISCUSSION

The control unit is tested at variable solar radiation and constant air temperature degree as given in Figure 15. Simulation is carried out by giving an irradiation changes from 500 W/m^2 to 1000 W/m^2 and constant temperature at 25°C . The different MPPT techniques are tested to check its ability to track the PV maximum power. Figure 16 gives the PV power, current and voltage waveforms simulated using P&O algorithm. The performance of IC technique is cleared in Figure 17. The two different FLC techniques give the output power of PV module equal to 74.4 W at 1000 W/m^2 and 34 W at 500 W/m^2 as shown in Figure 18 and Figure 19.

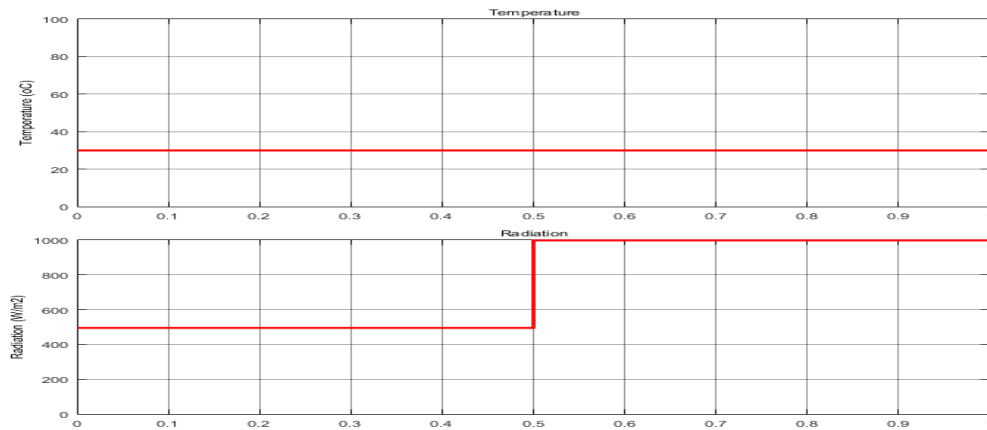


Figure 15. Variable solar radiation and constant air temperature

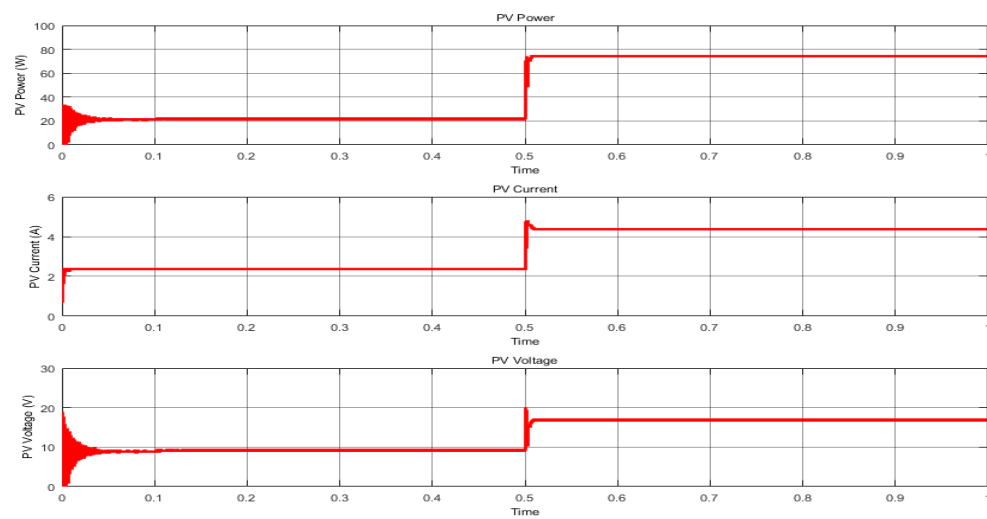


Figure 16. Power, voltage and current of PV for P&O technique

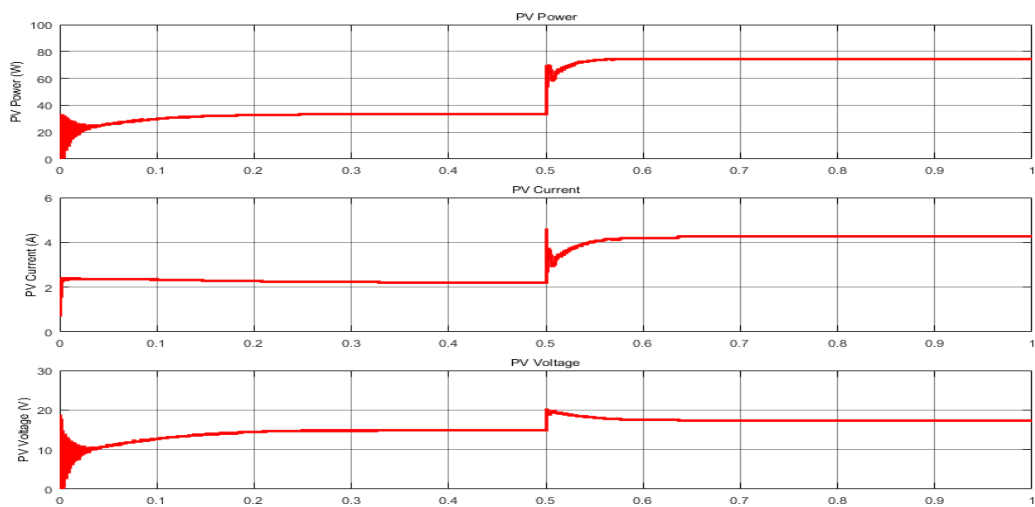


Figure 17. Power, voltage and current of PV for IC technique

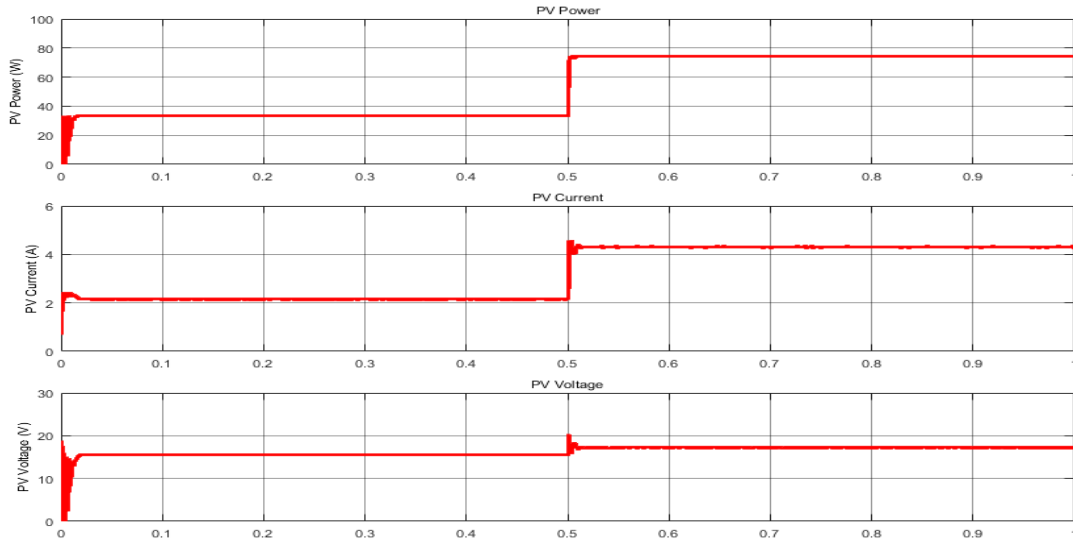


Figure 18. Power, voltage and current of PV for FLC toolbox

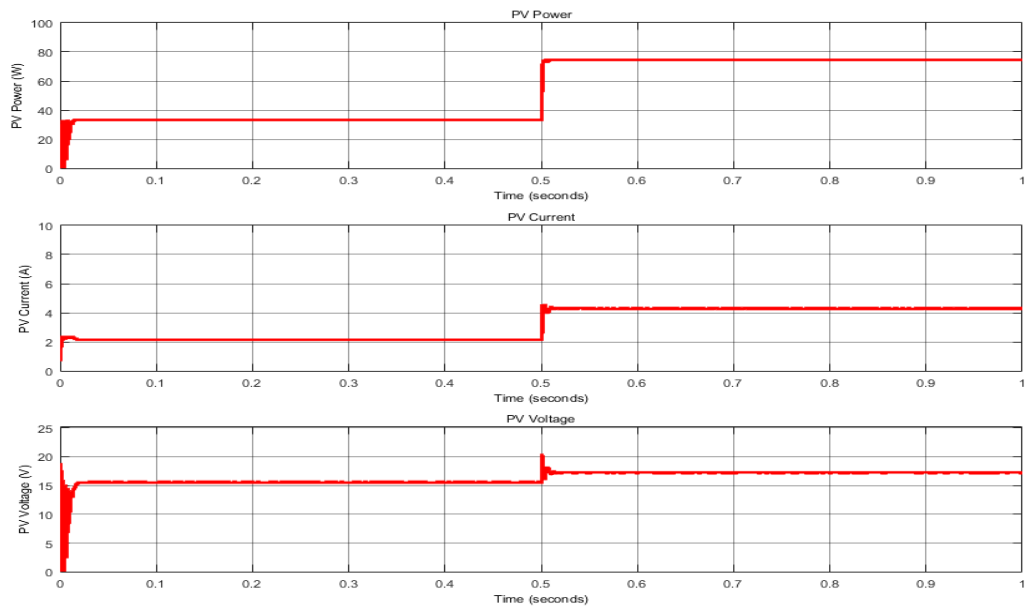


Figure 19. Power, voltage and current of PV for FLC Simulink

The FLC should be selected for its higher performance compared to the other controllers. FLC has better response time, less oscillation and much more accurate tracking at each step. The two different techniques of FLC have the same output response. So the mathematical model representation of FL is selected due to its simplicity for conversion to VHDL code. The first procedure in the conversion process from MATLAB SIMULINK to VHDL code is indicated in Figure 20. Once the FLC block diagram built in MATLAB/SIMULINK, it is converted to VHDL code, the converted VHDL code of the FLC subsystem is obtained in Fig. 21. Also, the VHDL code of the fuzzification, defuzzification, and rule base is shown in Figure 22, Figure 23 and Figure 24 respectively. The ISE Design Suite 14.6 software has been used for simulating the proposed architecture of FLC based on the VHDL as shown in Figure 25. The obtained results has been verified and compared with MATLAB. The simulation results approximately coincide with the simulation MATLAB results. In future the implementation of the proposed architecture will be implemented on FPGA chip.

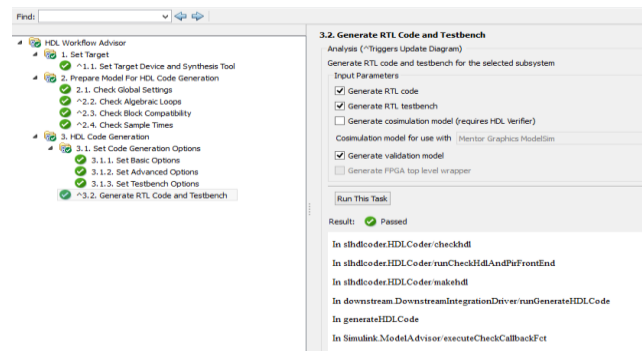


Figure 20. Conversion process from MATLAB SIMULINK to VHDL code

```

24 --
25 LIBRARY IEEE;
26 USE IEEE.std_logic_1164.ALL;
27 USE IEEE.numeric_std.ALL;
28
29 ENTITY Fuzzy_Subsystem IS
30   PORT( In2          : IN  real; -- double
31         In3          : IN  real; -- double
32         Out2         : OUT real; -- double
33         Out1         : OUT real; -- double
34   );
35 END Fuzzy_Subsystem;
36
37 ARCHITECTURE rtl OF Fuzzy_Subsystem IS
38
39   -- Component Declarations
40   COMPONENT Subsystem5
41   PORT( e          : IN  real; -- double
42         N5e        : IN  real; -- double
43         M5e        : IN  real; -- double
44         NSe        : IN  real; -- double
45         Ze         : IN  real; -- double
46         P5e        : IN  real; -- double
47         ...

```

Figure 21. VHDL code of the global subsystem of the FLC

```

92 ARCHITECTURE rtl OF Subsystem IS
93
94   -- Component Declarations
95   COMPONENT Subsystem5
96   PORT( x          : IN  real; -- double
97         x1         : IN  real; -- double
98         xt         : IN  real; -- double
99         x2         : IN  real; -- double
100        Out1       : OUT real; -- double
101   );
102 END COMPONENT;
103
104   COMPONENT Subsystem2
105   PORT( x          : IN  real; -- double
106         x1         : IN  real; -- double
107         xt         : IN  real; -- double
108         x2         : IN  real; -- double
109         Out1       : OUT real; -- double
110   );
111 END COMPONENT;
112
113   COMPONENT Subsystem11
114   PORT( x          : IN  real; -- double
115         x1         : IN  real; -- double
116         xt         : IN  real; -- double

```

Figure 22. VHDL code of the Fuzzification process

```

22 ENTITY Subsystem4_block1 IS
23   PORT( e1          : IN  real; -- double
24         NB         : IN  real; -- double
25         NM         : IN  real; -- double
26         NS         : IN  real; -- double
27         Z          : IN  real; -- double
28         PS         : IN  real; -- double
29         PM         : IN  real; -- double
30         PB         : IN  real; -- double
31         Out1       : OUT real; -- double
32         Out2       : OUT real; -- double
33         Out3       : OUT real; -- double
34         Out4       : OUT real; -- double
35         Out5       : OUT real; -- double
36         Out6       : OUT real; -- double
37         Out7       : OUT real; -- double
38   );
39 END Subsystem4_block1;
40
41 ARCHITECTURE rtl OF Subsystem4_block1 IS
42
43   -- Component Declarations
44   COMPONENT Subsystem5_block
45   PORT( x          : IN  real; -- double
46         x1         : IN  real; -- double

```

Figure 23. VHDL code of the deuzzification process

```

313 -- <S3>/Dot Product31
314 Dot_Product31_out1 <= In4 * In33;
315
316 -- <S3>/Dot Product32
317 Dot_Product32_out1 <= In5 * In34;
318
319 -- <S3>/Dot Product5
320 Dot_Product5_out1 <= In1 * In11;
321
322 -- <S3>/Dot Product6
323 Dot_Product6_out1 <= In1 * In12;
324
325 -- <S3>/Dot Product7
326 Dot_Product7_out1 <= In1 * In13;
327
328 -- <S3>/Dot Product8
329 Dot_Product8_out1 <= In3 * In14;
330
331 -- <S3>/Dot Product9
332 Dot_Product9_out1 <= In4 * In15;
333
334 -- <S3>/Dot Product33
335 Dot_Product33_out1 <= In5 * In35;

```

Figure 24. VHDL code of the Rulebase

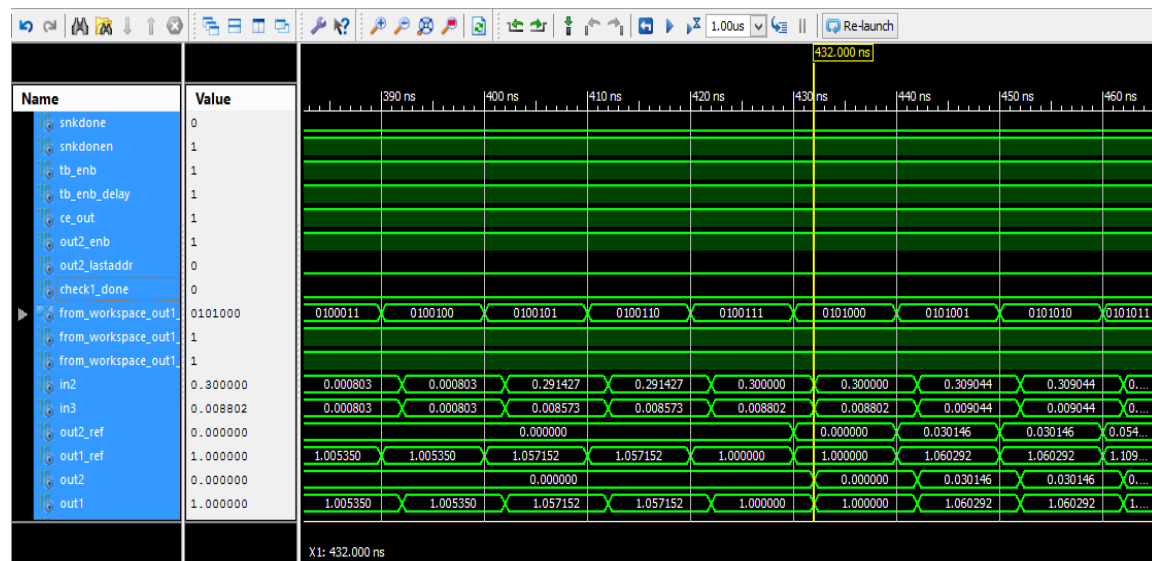


Figure 25. VHDL simulation of FLC subsystem

6. CONCLUSION

Photovoltaic stand-alone system simulation using Matlab/SIMULINK with a maximum power point tracking approach was presented in this paper. Also, several maximum power point tracking (MPPT) controller techniques were presented and implemented in Matlab/Simulink environment such as Perturb and Observe method (P&O), Incremental Conductance method (IC), and Fuzzy logic controller (FLC). The simulation results of FLC provided satisfactory results in extracting the MPP of PV compared with the other proposed controller techniques. The complete FLC was built in ISE design suite 14.6 software using very high speed integrated hardware description language to extract maximum power of the PV module. The simulation results validated the programs before downloading them on the FPGA. In future the implementation of the proposed architecture will be developed and implemented on FPGA chip.

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