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Stand-alone PV system with MPPT function based on fuzzy logic control for remote building applications

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ABSTRACT

Due to the limitations of reaching the grid utility to remote area, such as rural and/or countryside areas. Stand alone photovoltaic power systems represent good alternative that it can be adapted for electrical power delivering to these areas. In this paper, a new design of stand alone solar system suitable for individual building application is presented. This study focuses on proposing a desired solar PV panels matrix arrangement and connection, in addition to presenting an accurate design of Buck-Boost DC-DC converter which controlled by fuzzy logic controller FLC. The controller guarantees the maximum Power Point working conditions and manipulates the fluctuation of the DC link voltage of the matrix due to the weather changing. The main system includes battery bank charger, single phase inverter, and passive power filter. This study addresses the design and performance analysis the DC side of the 7.85 kW PV system. The system performance is evaluated through MATLAB/Simulink results which reflected the promising indications as an effective system for rural individual stand alone building applications.

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1. INTRODUCTION

Stand-alone solar systems are representing a high priority alternative to the grid utility for remote and rural areas. The solar energy availability and the zero cost of harvesting this energy in addition to the easy usage and other all are representing the merits of this source of energy [1, 2]. Solar energy can be converted into electrical power using the smaller unit in the solar system; this unit is solar cell which works on producing the desired output voltage or current through designing the arrangement of cells in the photovoltage PV panel [3]. Any desired value of electrical power (voltage, current) can be gained through designing the connection way among the solar photovoltaic panels. To have higher supplying voltage, PV panels should be connected in series where as to have higher supplying current, PV panels should be connected in parallel. For certain requirements of total voltage and current, PV panels can be connected in XY matrix that to guarantee the desired VI values [3-5].

In [6], a full design of a standalone photovoltaic system with high performance function is proposed. The system was manipulating the fluctuation of the DC link voltage which supplied from the PV panels to the system. Boost DC-DC converter is designed and simulated to overcome the variation in weather condition that to have stable suppled voltage as possible. Sinusoidal Pulse Width Modulation (SPWM) inverter is included in the system, the inverter is terminated by LCL-Filter to reduce the levels of the load current harmonic components.

When the number of the connected PV panels included in the PV matrix is big, the challenge of how has maximum possible electrical power from the incident solar energy that has higher priority in the system design. In the solar stand alone and even grid connected systems, the total quantity of the generated electrical power from PV matrix is affected by the nonlinearity of the solar panel with repect to the irradiation and ambent temperature [7]. To have the maximum power in the solar system, should be worked in a certain area of the PV panel considering the solar cell characteristics with respect to the output voltage, current, and power [8]. Many studies are focused on the algorithm effectiveness to have maximum power point tracking (MPPT) working conditions at the variation in weather condition, these algorthms such as algorithm of Perturb & Observe (P&O), algorithm of Incremental Conductance (IC), and short circuit current method [9-12]. For robust MPPT function, Fuzzy Logic Control (FLC) is demonstrating this effectiveness in many research studies [13-17]. In [13], FLC was included to enhance the performance of Hill-Climbing algorithm for MPPT objectives. New design and setting steps for accurate anf quick response FLC are proposed in [14-15], where as high stability system with fast tracking speed ability fuzzy logic controller are demonstrated in [16-17]. In [18-19] : accepted paper of IJPEDS], the effect of input and output variables' membership modifications on the quality of FLC performance is demonstrated by observing the performance effectiveness of Buck-Boost DC-DC converter.

Off-grid houses can help achieve the goal of providing electricity to remote places. Generating energy from PV cells is considered to be the best option for off-grid dwellings. However, the solar power generation is hindered by several factors like weather conditions, daylight and dust. The use of batteries as energy-storage devices is an option to provide energy when there is a lack of sun [20]. The advantages of working in standalone mode are many. Firstly, the dwelling unit is not dependent of the grid and is not affected by maintenance issues or blackouts. Secondly, energy savings are very important, not only for the owner, but for the overall consumption of countries. Finally, a new way of life is possible because isolated areas, where the cost of electric infrastructures would be high, can become an alternative to cities [21]. The challenges are also important such as, the economic feasibility of batteries for long periods of operation and the size of the devices required [22]. Based on the mentioned above, this paper proposes a new design of stand alone PV system for power supplying the remote buildings. The study focuses on the matching among PV panel's matrix arrangement, and the adopted type of DC-DC converter, and the high performance of fuzzy logic controller FLC during special memberships selection to have maximum power point MPP working condition for harvesting MPP power reaches to 7.85 kW. In Figure 1 a full design of a standalone photovoltaic system with high performance function is proposed.

The remaining of this study is as follows: Current-voltage and power-voltage characteristics of the designed PV matrix are shown and analyzed in Section II. Section III shows and explains the proposed stand alone system. Full design of a Boost-Buck DC-DC converter based on FLC is explained in Section IV. Simulation results are presented and analyzed in section V. The summary of findings is presented and concluded in section VI.

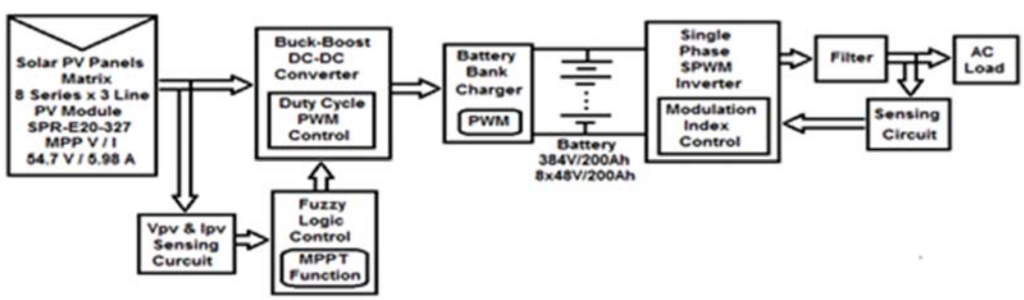


Figure 1. Main block diagram of the solar stand alone system

2. SYSTEM DISCRIPTION

Figure 1 shows the main block diagram of the proposed stand alone system. First block is represented by PV matrix which includes 24 panels. These panels are arranged as 3 parallel lines each line includes 8 panels serially connected, more detailed about the PV matrix will be described in the next section. The values of output PV matrix voltage and current will be measured by sensing circuit that to be entered the fuzzy logic controller (FLC) for MPPT function. The controller is controlling the duty cycle of the Buck-Boost DC-DC converter power electronic switch by pulse width modulation (PWM) strategy. The remaining blocks are represented by PWM battery charger; set of serial connection includes 8 of 48V/200Ah batteries which supplies the Sinusoidal PWM signle phase inverter to invert the entered DC link voltage to AC voltage. The inverter is terminated by low pass passive power filter for high order harmnoics attenuating before delivering the AC voltage to the AC connected load. The inverter output voltage will be sensed by sensing circuit that to be used for modulation index control to stabilize the inverter AC voltage level.

3. PHOTOVOLTAIC PANELS MATRIX

The design of the photovoltaic panel matrix is started by selecting PV panel module SPR-E20-327 of 96 solar cells type Monocrystalline Maxeon Gen II of efficiency 20.4%, Table 1 summerizes the specifications of the PV matrix and the selected PV panel parameters as well.

Table 1. Spicefications of the designed PV matrix and the selected PV module SPR-E20-327

Parameter	Value
Number of series panels	8
Number of parallel PV lines	3
Nominal Power (Pnom)	327 W
Power Tolerance	+5/–0%
Avg. Panel Efficiency	20.4%
Rated Voltage (Vmpp)	54.7 V
Rated Current (Impp)	5.98 A
Open-Circuit Voltage (Voc)	64.9 V
Short-Circuit Current (Isc)	6.46 A
Max. System Voltage	600 V UL & 1000 V IEC
Maximum Series Fuse	15 A
Power Temp Coef.	–0.35% / º C
Voltage Temp Coef.	–176.6 mV / º C
Current Temp Coef.	2.6 mA / º C

Each PV panel in the matric includes another matrix of solar cells; these cells are producing a certain electrical power proportional upon the falling sunlight intensity and inversely proportional with ambient temperature value through nonlinear relationships. In other words, the value of instantaneous output voltage and current from the PV panel are nonliearly proportional with the mentioned environmental parameters as shown in terms (1) to (4) with respect to the equivalent electrical circuit of the solar cell [4-12], [17] when I_D represents the diode current, I_{SC} represents the total light generated current, I_{PV} represents the output current of the PV panel, R_P represents the shunt resistor, and R_S represents the serial resistor all shown in Figure 2. The arrangement of the PV panel matrix is illustrated in Figure 3, the proposed arrangement works at maximum Power Point condition on producing ourput voltage upto 437.6 V whereas the output current can reach up to 17.94 A. The total rated power at the MPP conditions can be reach to 7.85 kW.

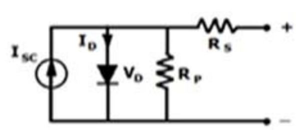


Figure 2. Electrical circuit of solar PV cell

$$I_D = I_0\left(e^{\frac{V_D}{V_T}} - 1\right) \tag{1}$$

$$V_{PV} = V_D - R_S I_{PV} \tag{2}$$

$$I_{SC} = I_D + \frac{V_D}{R_P} + I_{PV} \tag{3}$$

$$I_{PV} = I_{SC} - I_D - \frac{V_D}{R_P} \tag{4}$$

$$V_{PVtotal} = No.of\ Serial\ Panels * V_{PV} \quad (5)$$
$$I_{PVtotal} = No.of\ Parallel\ PV\ lines * I_{PV} \quad (6)$$

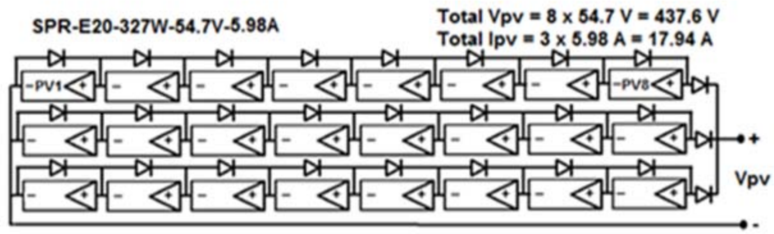
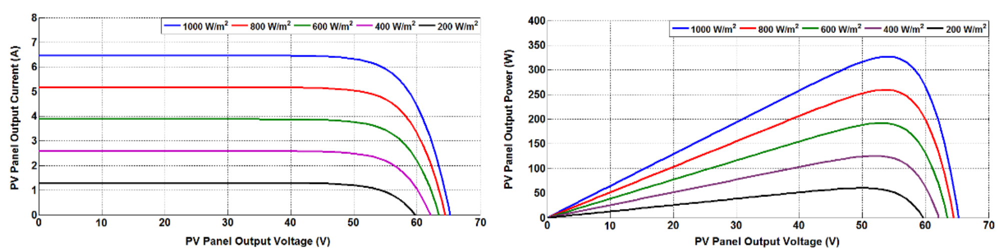


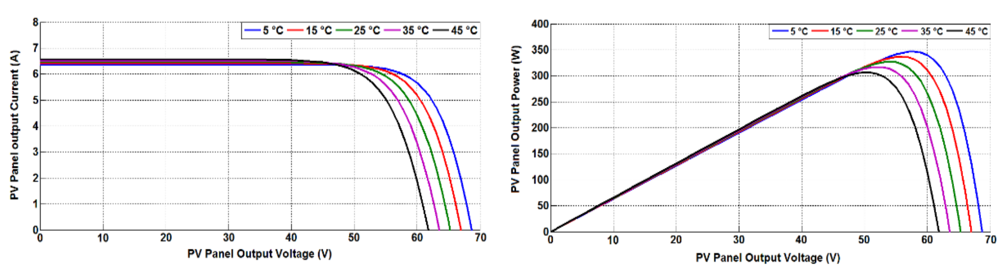
Figure 3. The designed PV panel matrix

The selected PV panel characteristics of I-V and P-V are demonstrated in Figure 4 and Figure 5 respectively for 5 levels of light irradiation condition and 5 levels of imbent temperature. From these figures, the positive proportion of the output power quantity wit respect to the light intensity is clearly noticeable whereas the inverse propotion of the output power is noticeable with respect to embint temperature. Figure 6 shows I-V and P-V characteristics of the solar PV matrix of (SPR-E20-327) modules at fixed irradiation level of 1000 W/m2 and imbent temperature of 25 °C. Figure 6 demonstrates the importance of working at maximum power point conditions for the PV matrix that to guarantee harvesting the higher sopar power quantity whereas the total output voltage and current are equal the summation of 8 PV panels serially connected and 3 lines parallel connected respivtively as explained in (5), and (6).



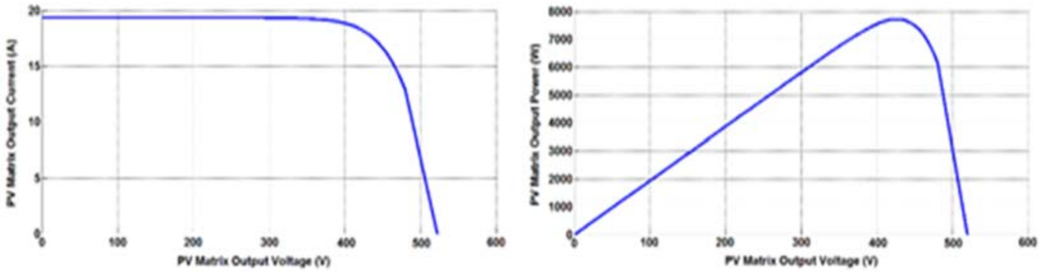
(a) (b)

Figure 4. The solar PV module (SPR-E20-327) characteristicsat fixed imbent temperature of 25 °C; (a) I-V characteristics at different irradiation levels. (b) P-V characteristics at same irradiation levels.



(a) (b)

Figure 5. The solar PV module (SPR-E20-327) characteristicsat fixed irradiation level of 1000 W/m^2; (a) I-V characteristics at different imbent temperature levels. (b) P-V characteristics at same imbent temperature levels.



(a) (b)

Figure 6. The solar PV matrix of MPP power 7.85 kW using 8x3 (SPR-E20-327) modules characteristics at fixed irradiation level of 1000 W/m^2 and fixed imbent temperature of 25 °C; (a) I-V characteristics (b) P-V characteristics .

4. BUCK-BOOST DC-DC CONVERTER

This converter is stepping-up (Boost), or stepping-down (Buck) the output voltage. Based on pulse width modulation strategy [19], [23-26], the duty cycle (D) of the gate drive pulses can be controlled to control the duty time of the connected power electronic switch. The relation of the converter output voltage (V_o) with respect to the converter input voltage (V_{in}) and the duty cylcle *D* of the converter switch is explained in (7). For stepping down the input voltage, *D* should be less than 0.5, the converter in this condition works as buck converter. For stepping up the input voltage, *D* should be greater than 0.5, and the converter works as boost converter [18].

$$V_o = -V_{in}\left(\frac{D}{1-D}\right) \tag{7}$$

Continuous Conduction Mode (CCM) is adopted in this study as a working mode for the converter, and the converter components are designed based on the studies of [6], [18]. For switching frequency *f*, and load resistor *R*, the minimum value of the inductor can be calculated by (8).

$$L_{min} = \frac{R\,(1-D)^2}{2f} \tag{8}$$

To work in this CCM mode, the inductor value should be greater than minimum value. On the other side, the minimum converter capacitor *C* is limited by the output voltage V_O, the output voltage ripple ΔV_O, duty cycle *D*, switching frequency *f* and load resistor *R* as shown in (9).

$$C = \frac{D}{R\,f}\frac{V_O}{\Delta V_O} \tag{9}$$

Due to the level of the required power (7.85 kW) which represents high level required to be delivered from the converter, in order to reduce the stress on the switch (Insulated Gate Bipolar Transistor IGBT), the selected switching frequency is 5 kHz. The minimum calculated value of the inductor and the capacitor values at the selected switching frequency, and at voltage ripple ($\Delta V_O/V_O$) of 2%, with $D = 0.5$, for load resistance of (437.6V^2/7850W) = 24.39Ω are 0.62 mH, and 205 µF respectively. For simulation process, the selected values of the inductor and capacitor in the Buck-Boost DC-DC converter are 1 mH, and 470 µF respectively. Figure 7 shows the diagram of the designed Buck-Boost DC-DC converter which controlled by Fuzzy logic Controller (FLC). PV matrix represents a first part which supplies the DC electricity to the converter. FLC is designed to guarantee the MPPT working conditions for the converter during the weather variation conditions.

5. FUZZY LOGIC CONTROLLER

Based on the merits of the robustness and the quick controlling and tracking response of FLC as mentioned in the previous studies, this controller is selected to capture the MPPT working condition for the converter during the weather varying. The instantaneous voltage and current values of solar panel are receiving as first step of the controlling function process. The instantaneous output power from PV matrix can be calculated by (10), then the difference between each two successive powers and voltages can be calculated by (11), and (12) respectively. The rate of powers change to the voltages change represents the variable of error *Er(k)* which shown in (13) whereas and the change of error variables can be represented by *ΔEr(k)* shown in (14). FLC will decide the additional value change of duty cycle *ΔD* to the initial constant duty cycle D=0.5 by evaluating the instantaneous values and the trends of the input variables to the controller [27-28]. Based on the principle of PWM strategy, Controlling *D* controls the instantaneous value of the converter output voltage. Based on the fact of that the MPP point is located at top position of the power curve with respect to the PV voltage, at this location of maximum power, the power change to the voltage change equals to zero (*ΔP/ΔV* = 0). Figure 8 shows the location of MPP point in addition to the the blocks of the FLC process.

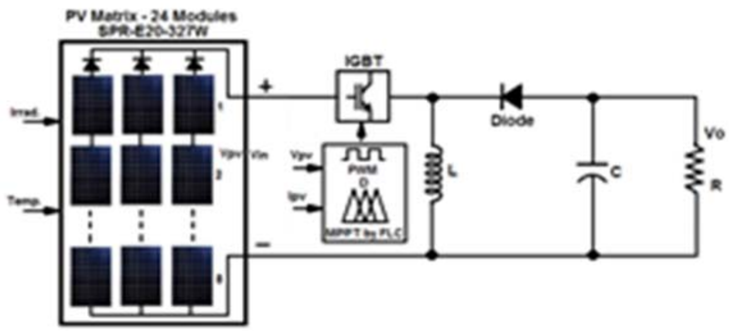


Figure 7. PV matrix with Buck-Boost DC-DC converter arrangement

$$P(k) = V(k) * I(k) \tag{10}$$

$$\Delta P(k) = P(k) - P(k-1) \tag{11}$$

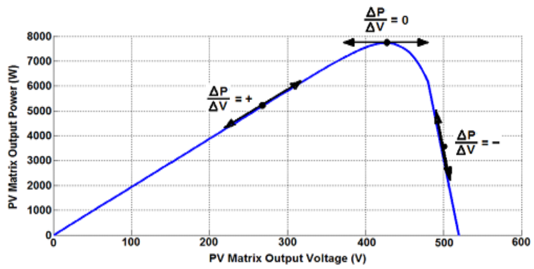
$$\Delta V(k) = V(k) - V(k-1) \tag{12}$$

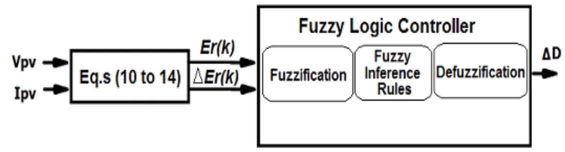
$$Er(k) = \frac{\Delta P(k)}{\Delta V(k)} \tag{13}$$

$$\Delta Er(k) = Er(k) - Er(k-1) \tag{14}$$

5.1 Fuzzy logic controller blocks

As shown in Figure 8 (b), the controller includes Fuzzification block, and Fuzzy Inference Rules block, then the Defuzzification block. The design of these FLC blocks directly effect the effectiveness of the controller. Fuzzification Block: this block recieves the input variables in realistic domain format and converts it to linguistic variables understandable by the next FLC blocks. The input linguistic variable of the error *Er(k)* is represented by five levels: NB (Negative Big), NS (Negative Small), ZR (Zero Level), PS (Positive Small), and PB (Positive Big). The input linguistic variable of the error change *ΔEr* is represented by three levels: NS (Negative Small), ZR (Zero Level), and PS (Positive Small). The output linguistic variable names are designed by five changes in the duty cycle level *ΔD*: NB (Negative Big), NS (Negative Small), ZR (Zero Change), PS (Positive Small), and PB (Positive Big) change. Fuzzy Inference Rules Block: mamdani method is used to design this block which includs the designed inference rules that adopted to guarantee a fast traking function of the proposed controller to the point of maximum power can harvesting from the photovoltaiv matrix. Defuzzification Block: this block produces the realistic value of the change in the duty cycle *ΔD* based on the center of gravity method. The converter is bucking or boosting the output voltage by subtract or add the duty cycle change respectively based on the polarity of *ΔD* to track the MPP point.





(a) (b)

Figure 8. Function of the fuzzy logic controller FLC: (a) maximum power point traking (MPPT), (b) FLC blocks and process.

5.2 FLC blocks design

This section shows the details of membership design of the input and output variables with respect to the proposed inference rules. These rules are shown in Table II whereas Figure 9 shows the designed memberships of power error *Er(k)*, error change *ΔEr(k)*, duty cycle change *ΔD (n)*, memberships surface view, and the load power for different irradiation levels (600, 1000, 800, 600) W/m2. The effectiveness of FLC is clearly demonstrated through capturing the MPP for all of the mentioned irradiation levels by focusing around zero error position for full interval of 4 secons divided into four equal intervals of 1 second.

Table 2. FLC Fuzzy Inference Rules

No	If	Then
1	(er is NB) and (Der is NB)	(DD is ZR)
2	(er is NB) and (Der is NS)	(DD is ZR)
3	(er is NB) and (Der is ZR)	(DD is NB)
4	(er is NS) and (Der is NB)	(DD is ZR)
5	(er is NS) and (Der is ZR)	(DD is NS)
6	(er is NS) and (Der is PB)	(DD is NS)
7	(er is ZR) and (Der is NB)	(DD is NS)
8	(er is ZR) and (Der is ZR)	(DD is ZR)
9	(er is ZR) and (Der is PB)	(DD is PS)
10	(er is PS) and (Der is NB)	(DD is PS)
11	(er is PS) and (Der is ZR)	(DD is PS)
12	(er is PS) and (Der is PB)	(DD is ZR)
13	(er is PB) and (Der is NB)	(DD is PB)
14	(er is PB) and (Der is ZR)	(DD is PB)
15	(er is PB) and (Der is PB)	(DD is ZR)
16	(er is NB) and (Der is PS)	(DD is NB)
17	(er is NB) and (Der is PB)	(DD is NB)
18	(er is NS) and (Der is NS)	(DD is ZR)
19	(er is NS) and (Der is PS)	(DD is NS)
20	(er is ZR) and (Der is NS)	(DD is ZR)
21	(er is ZR) and (Der is PS)	(DD is ZR)
22	(er is PS) and (Der is NS)	(DD is PS)
23	(er is PS) and (Der is PS)	(DD is ZR)
24	(er is PB) and (Der is NS)	(DD is PB)
25	(er is PB) and (Der is PS)	(DD is ZR)

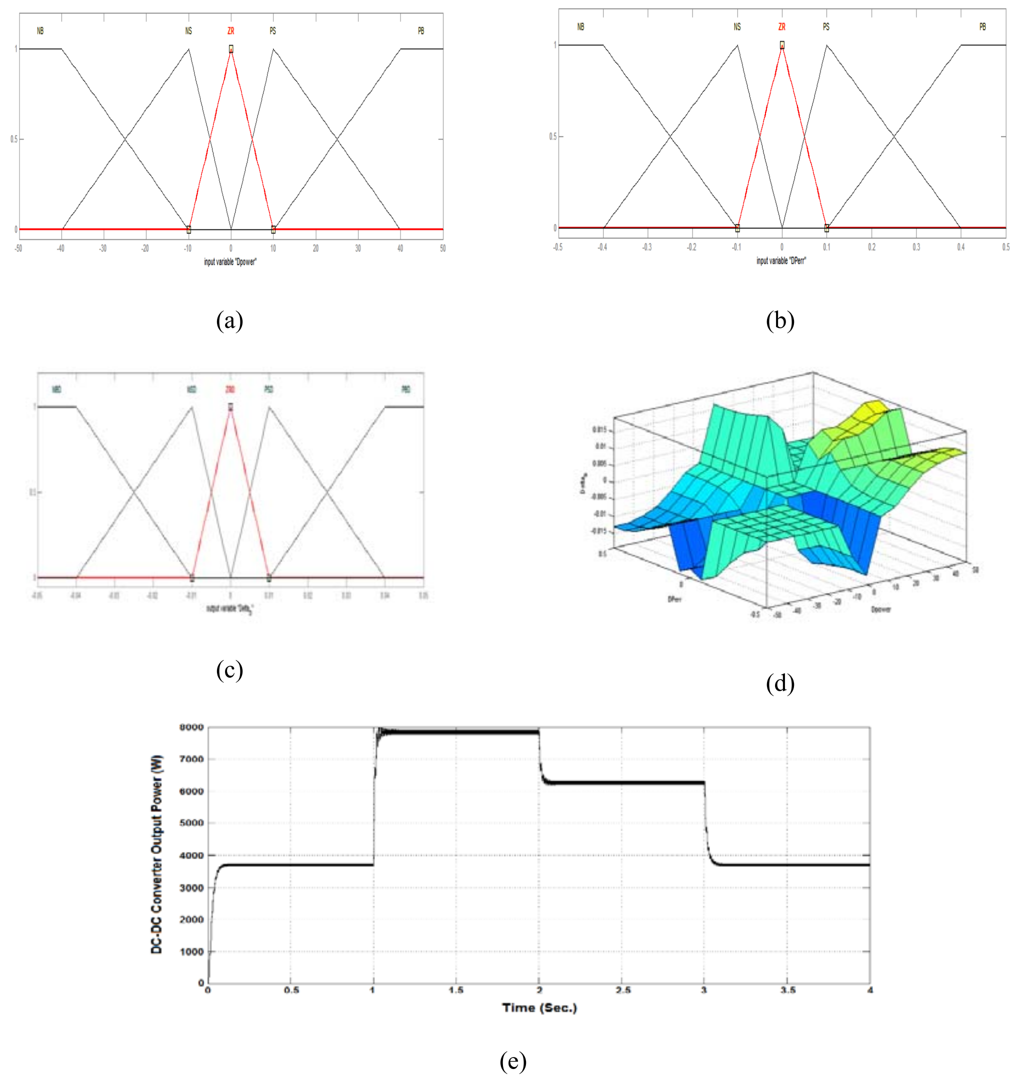


Figure 9. FLC blocks variables for MPPT function from top to down; (a) membership function of input variable power error, (b) membership function of input variable power error change, (c) membership function of output variable duty cycle change DeltaD (k), (d) all memberships' surface view, (e) quantity of output power from DC-DC converter.

6. CONCLUSION

This study proposed a stand alone solar system with in details firstly in terms of architecture design, building shape and dimentions, then in terms of electrical aspects. A full electrical and electronic design is presented by main block diagram, then a detailed design with simulation investigating are done for the solar PV panels matrix design, Buck-Boost DC-DC converter. By focusing in the memberships shape around Zero error position, Fuzzy Logic Controller FLC is designed to guarantee the required working conditions of Maximum Power Point Tracking MPPT function. Simulation results reflect the effectiveness of the proposed solution for the mentioned objective of harvesting the maximum power at different irradiation levels and specially harvesting 7.85 kW when the irradiation level 1000 W/m^2.

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