Design and PIL Implementation of Fuzzy Logic-based MPPT Control for Symmetrical Multilevel Boost Converter

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Abstract: - This paper aims to introduce a fuzzy logic adaptive MPPT controller to control a symmetrical multilevel converter in a standalone PV system. The system is evaluated under fixed and variable solar radiation with 15 V as the input voltage 60 V as the required output voltage and 50 kHz as the switching frequency. Results prove that by using the controller, the system successfully tracks the MPPT point for constant and variable radiation without oscillation around the maximum power point. In addition, the overshoot and time response is reduced while the voltage ripples are eliminated. The proposed controller is verified through practical implementation in Arduino mega board to test the accuracy of results. The practical finding via a processor in the loop test validates the simulation results.

Key-Words: - Fuzzy logic, symmetrical multilevel converter, boost converter, Maximum power point tracking, photovoltaic system, efficiency.

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1 Introduction

The use of renewable energy sources (RES) has become essential to achieve the energy transition and to respond to the continuously increased consumption of electrical energy based on fossil fuel sources. However, fossil fuel potential is steadily decreasing which reinforces the research to find efficient solutions. The integration of RES to power different sectors including building and industry is still limited due to several issues namely, the low efficiency of renewable energy systems(RESs) and its intermittency. For these reasons, power converters were introduced as interface devices dedicated to enhancing the performance of RESs, [1], [2]. Converters give the ability to adjust the voltage from high to low levels and vice-versa through the converter features depending on the circuit diagram and its design, [3]. Indeed, there are two main categories of converters: non-isolated and isolated converters. On one hand, the non-isolated converters are transformer-less converters including coupled inductor boost converters, interleaved converters, and integrated boost converters which are widely used due to their simplicity and efficiency, [4]. On the other hand, isolated converters are transformer-based converters including Fly-back converters, half-bridge, full-bridge, and push-pull, [5]. Despite, the extensive enhancement in converter topologies, some limitations still occur in conventional converters such as high voltage and current ripples, high voltage switches, and high power losses which damage load and energy protection, [6], [7].

As a consequence, research has been conducted to overcome these limitations through the development of new converter topologies. Multilevel converters are introduced as proposed solutions to overcome the drawbacks of the conventional boost converter. They are used in several applications involving (RESs), electric vehicles (EV), and battery energy storage systems (BESS) due to their ability to reduce switching losses as well as voltage and current ripples and voltage stress, [8], [9]. Among the proposed converters, a symmetrical multilevel converter (SML) has been developed for PV panel systems giving the advantages of low input current and capacitor voltage helping to protect the nonlinear source, [10]. In addition to these advantages, the SML converter reduces the output voltage transient overshoot to 46.32 % and minimizes the output voltage and current ripples to 0.68% and 0.44% with high efficiency reaching 97% compared to the classic boost converter, [11], [12]. All of the previously cited research discussed the response of the SML under open loop system mode. Nevertheless, DC/DC converter implementation in PV systems and other applications requires the analysis of the system under closed-loop mode. Based on these reasons, it is crucial to study the control of the SML converter under a closed-loop mode system. Several controllers are proposed in the literature to control converters including the perturb and observe (P&O), fuzzy logic controller, sliding mode control, and GSS-based MPPT control, [9], [13], [14], [15]. However, the control of multilevel converters is still presenting a crucial issue prohibiting the use of multilevel converters in several applications. In addition, in the literature, most papers focus on the classic boost converter as a conversion device in PV systems which limits the efficiency of the systems controlled due to the classic boost converter limitations. For this reason, the use of non-classic topologies in PV systems is highly recommended to improve the system's efficiency based on both aspects: converter improvement and controller robustness. This paper uses a non-classic boost converter topology as a conversion device, the symmetrical multilevel converter, and improves its performance response through the design of a new controller, a fuzzy logic-based MPPT controller, to be used in standalone PV systems. The system performance is tested under constant and variated radiation using the Matlab/ Simulink software. In addition, the paper aims to validate the simulation results via the process in loop test using Arduino Mega board.

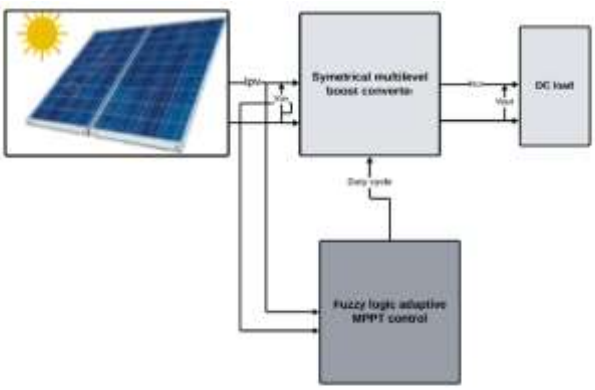

Fig. 1: the proposed stand-alone system with a symmetrical multilevel converter

The standalone system consists of a solar PV generator linked to a DC load using the SML as an interface to boost the voltage via fuzzy logic-based MPPT controller as shown in Figure 1.

2 Problem Formulation

2.1 Solar PV system

The PV system is presented by a simple module as shown in Figure 2. The current source serves as an equivalent of the PV cell. The photocurrent I_{pv} depends on the irradiance G and the cell temperature (T_C). The resistance R_s indicates the losses due to the contacts and the connection. The parallel resistance, R_p, reflects the diode's leakage currents, [16].

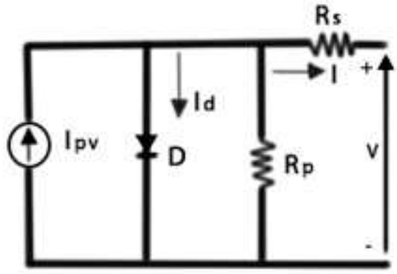

Fig. 2: Model of single solar PV cell

Based on equation (1), the PV cell could be simulated in Matlab/ Simulink software.

$$I = I_{PV} - I_S\left(exp\frac{q(V+R_S I)}{N_S k T_a} - 1\right) - \frac{V+R_S I}{R_P} \qquad (1)$$

Where I_s represents the saturation current, q is the electron charge, k is the constant of the Boltzmann gas and N_s is the idealizing factor of the diode. The I_{PV} is the photocurrent current of the PV cell.

2.2 Symmetrical Multilevel Boost Converter Operation

The SML dc-dc converter is proposed by [10]. it provides the ripple reduction capability. It is developed using two differently linked multilevel boost converters. The first converter which is the converter's upper side comprises a power switch (T_1), an inductor (L_1), three capacitors (C_1, C_2, and C_3), and three diodes (D_1, D_2, and D_3). The capacitors C_2 and C_3 generate the initial floating output. The bottom side of the converter is a reversed version of the top converter, including a power switch (T_2), an inductor (L_2), three capacitors (C_4, C_5, and C_6), and three diodes (D_4, D_5, and D_6). The capacitors C_5 and C_6 generate another floating output. The load is linked differentially to the upper and lower floating outputs. The diagram of SML is shown in Figure 3.

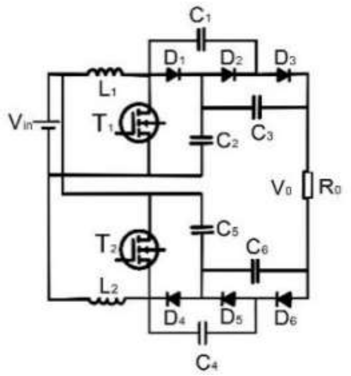

Fig. 3: The diagram of the symmetrical multilevel boost converter

The converter operates under four states depending on the conditions of both switches T_1 and T_2. The states of T_1, and T_2, take two hypotheses on or OFF as presented in Table 1.

Table 1. Symmetrical multilevel converter functioning steps

State	Switch T_1	Switch T_2
State 1	ON	OFF
State 2	OFF	ON
State 3	OFF	OFF
State 4	ON	ON

2.3 The Design of Symmetrical Multilevel Boost

The SML converter is set to be implemented in a standalone PV system powered by a PV generator with 630 W as the maximum power for one module. The output voltage of the PV generator is varying according to the irradiation variation. It ranges from 10V to 15 V. The standalone system is designed to give 60V to 64V as output voltage with 50 kHz as frequency. The design of the SML is done based on the following formulas (2)-(11), [10]:

$$V_{out} = \frac{(3-D_1-D_2-D_1*D_2)}{(D_1-1)(D_2-1)}Vin \quad (2)$$

Where D_1 and D_2 represent the duty cycle of switch T_1 and switch T_2

$$L_1 = \frac{V_{in}}{\Delta i_{L1} f_s} D_1 \quad (3)$$

$$L_2 = \frac{V_{in}}{\Delta i_{L2} f_s} D_2 \quad (4)$$

$$C_1 = \frac{V_o}{f \Delta V_{C1} R} \quad (5)$$

$$C_2 = \frac{V_o}{f \Delta V_{C1} R} \quad (6)$$

$$C_2 = \frac{(1+D_1)}{f \Delta V_{C2} R} \quad (7)$$

$$C_3 = \frac{D_1 V_o}{f \Delta V_{C3} R} \quad (8)$$

$$C_4 = \frac{D_2 V_o}{(1-D_2) f \Delta V_{C4} R} \quad (9)$$

$$C_5 = \frac{(1+D_2) D_2 V_o}{(1-D_2) f \Delta V_{C4} R} \quad (10)$$

$$C_6 = \frac{D_2^2 V_o}{(1-D_2) f \Delta V_{C6} R} \quad (11)$$

2.4 The SML Converter Controller

The PV generator output power depends on temperature and irradiance giving a non-irregular behavior of energy served to the load. For this reason, it is crucial to introduce an adaptive interface between the PV generator and load which is in our case the boost converter namely the SML. However, a control device is vital to maintain the output voltage of the SML at the required level.

In addition, the PV generator is characterized by a maximum power point where the voltage and power of the PV generator are at their maximum as shown in Figure 4.

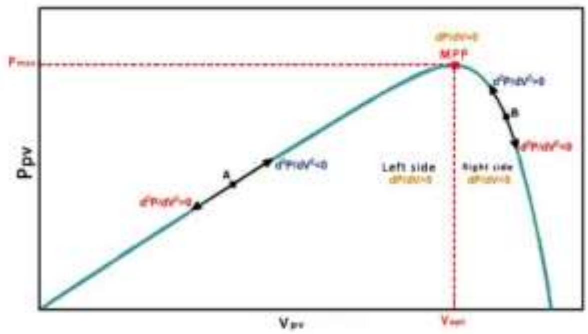

Fig. 4: Monitoring of the MPP direction

As a result, to get high efficiency of the system, it is vital to ensure that the controller of the system is keeping the PV generator functioning at its MPP. The control algorithm is built based on the monitoring of the MPP and its variations which are voltage and power of the PV system. In this context, numerous algorithms are introduced to track the maximum power point for RESs including the Perturb& observe (P&O), Hill climbing (HC), Fuzzy logic control (FLC), and Incremental conductance (IC), [17]. Multilevel converters are known for the difficulty of their control, due to the fact that most control algorithms require a mathematical modeling of the converter. Due to the non-linearity of the converter, it is difficult to find an exact mathematical model.

The FLC adaptive MPPT control is chosen to control the SML for the following reasons: The fuzzy logic controller is characterized by several advantages: its resilience compared to traditional nonlinear controllers, its ability to operate with imprecise inputs, and the management of nonlinearity; in addition, the FLC do not require an exact mathematical model to control the converter. It works based on three steps: The inference engine with a rule base, the defuzzifier at the output terminal, and the fuzzifier unit at the input terminal, [18], [19].

2.5 Fuzzy Logic-Based MPPT Technique Controller

A fuzzy logic controller is a nonlinear controller. It includes three steps: Fuzzification, Rule base, and defuzzification which are illustrated in Figure 5, [20].

- **Fuzzification**: Each entry is mapped to the degree of the function to which it belongs. This mapping is performed according to conditions given by the rule base. For each linguistic term that applies to the input variable, a degree of membership exists.
- **Rule base**: A rule base is a number of rules defined by the user to produce the final signal according to its comprehension of the system behavior. The rules used in fuzzy logic controllers are generally "if-then" statements, where "if" is the condition and "then" represents the response. For the designed system, rules are concluded by the monitoring of the PV system MPP observation. Based on the measured inputs, i.e. Power variation (dP/dV) and its derivative (d^2P/dV^2), simulation software executes these rules and issues an output variation of the duty cycle, i.e. (Δd) to get finally a control signal. Indeed, the Mamdani method is used to find the output of the inference. each of the inputs admits a boolean variation as follows:
  The variation of the power source (dP/dV) admits five linguistic variables which are (Negative Big, Negative Small, Zero, Positive, and Very Positive) while its derivative has three variations d^2P/dV^2(Negative, Zero, Positive) as it indicated in Table 2. The output values are produced by the combination of the application of rules based on the Mamdani method.
- **Defuzzification:** In this block, fuzzy control actions are transformed into crisp signals, [21].

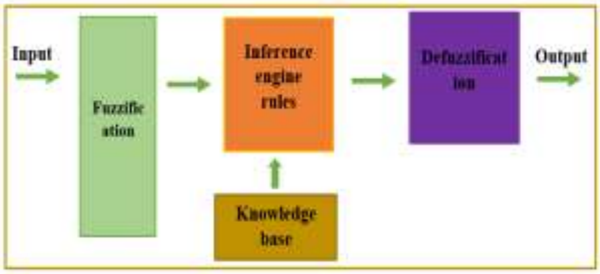

Fig. 5: Fuzzy logic controller bloc diagram schema

Table 2. Rules of Duty Cycle Variation ΔD

ΔD		(dPpv/dVpv)'		
		Negative	Zero	Positive
dP_{PV}/dV_{PV}	NB	3%	3%	3%
	NS	3%	1%	1%
	ZE	0%	0%	0%
	PS	-1%	-1%	-3%
	PB	-3%	-3%	-3%

The following flowchart, shown in Figure 6, demonstrates the methodology to control the system with the combination of MPPT and fuzzy logic control principles.

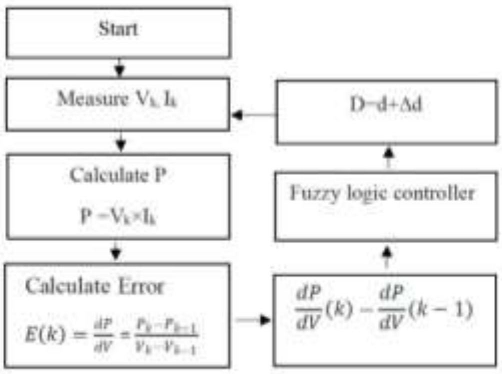

Fig. 6: Fuzzy logic-based MPPT flowchart algorithm

3 Problem Solution

The evaluation of the SML converter behavior is done during constant solar radiation and variable solar radiation. The SML, in the two cases, is powered by a PV solar panel giving an input voltage of V_{pv}= 15 V. The converter is evaluated under the same circumstance for both processes and with the same component sizing to find accurate results concerning the use of the fuzzy logic adaptive

MPPT controller. The simulation is done using Matlab/Simulink software as shown in Figure 7.

3.1 Simulation Results with Fixed Solar Radiation

At the first stage, the solar radiation is fixed to 1000 W/m^2, As a result, the power panel supplies the converter with 15 V as V_{pv}. The output voltage of the SML converter reaches 66.46 V as shown in Figure 8. The system design in closed loop mode succeeded in producing an output voltage in the range of the required output voltage during the design phase . The output voltage found is also characterized by the elimination of ripples, fast-rising, and settling time given 4.5 and 6.353 ms respectively. In addition, it provides a very low overshoot with 0.466% of the output voltage final value. The output voltage obtained by using the fuzzy logic adaptive MPPT control gives more efficient and accurate results by ensuring the stability, robustness, and fast response of the system output.

Figure 9 shows the output current and input current of the system. It is proved that the controller could provide low output current gain and ripples.

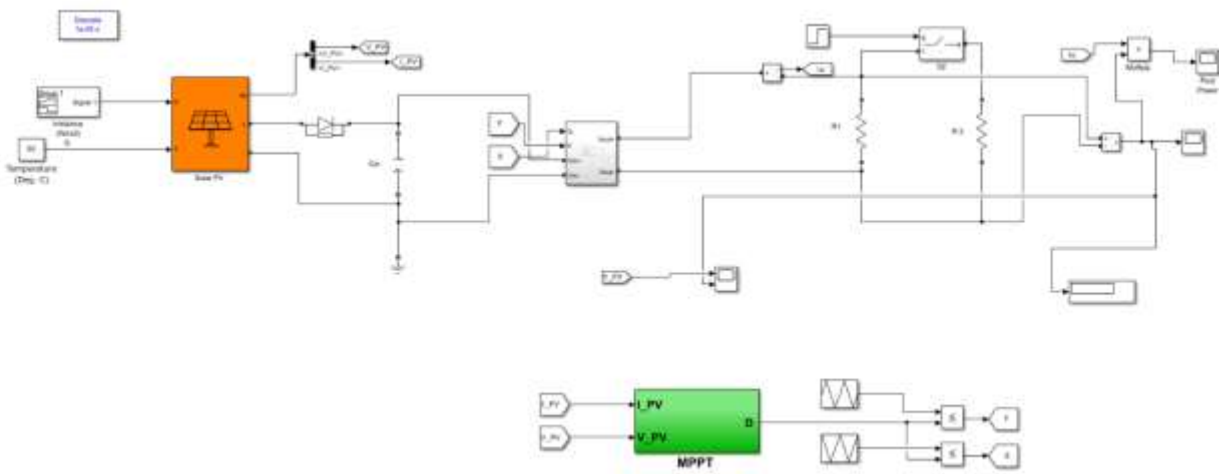

Fig. 7: Schematic diagram of the SML converter with Fuzzy logic based MPPT control

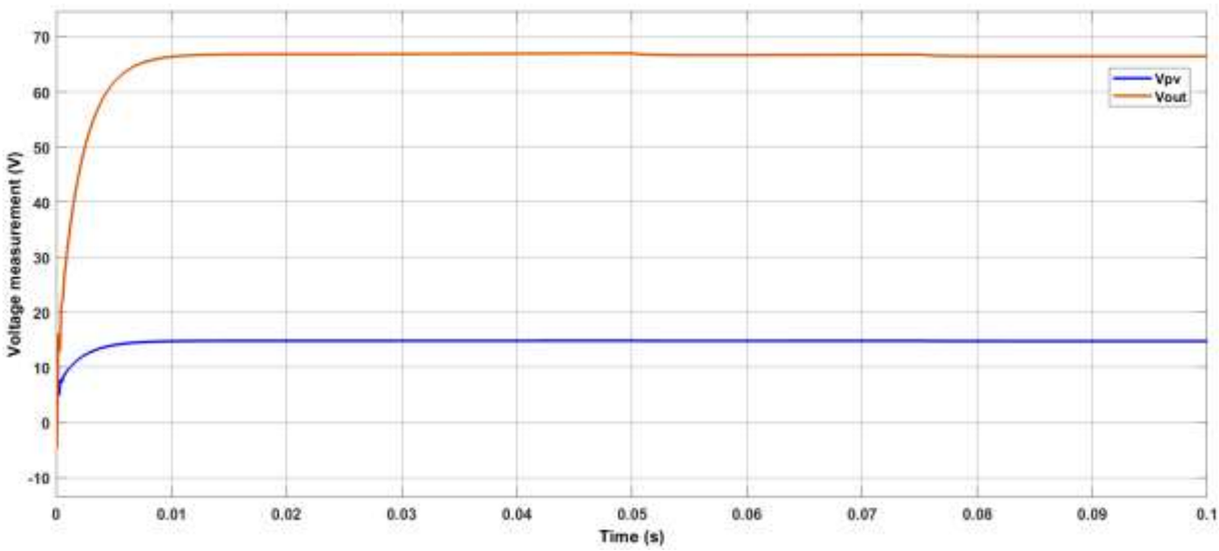

Fig. 8: The SML voltage measurement results using the Fuzzy logic MPPT technique under fixed solar radiation: V_{out}, and V_{pv}

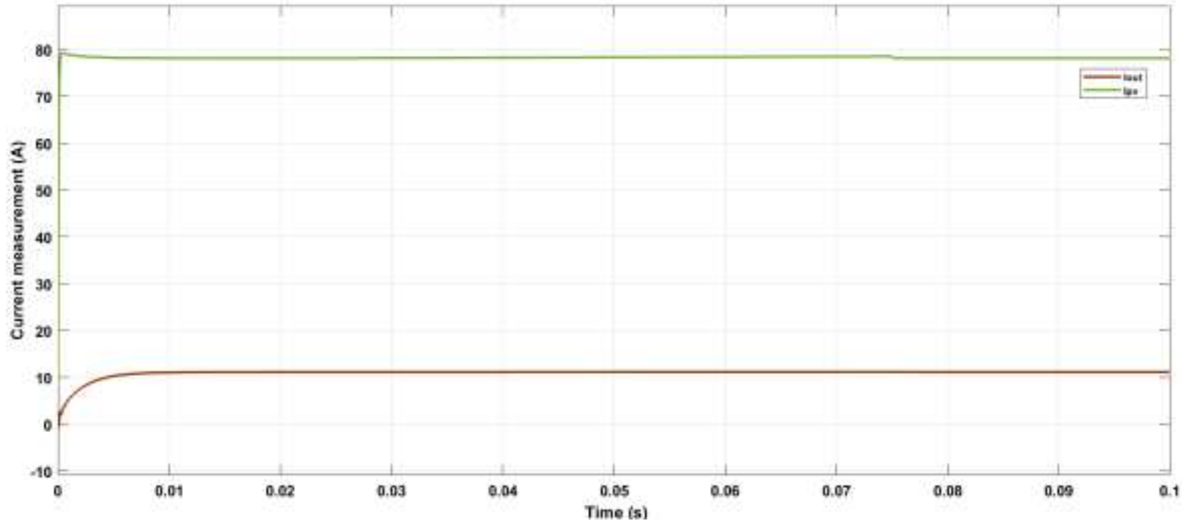

Fig. 9: The SML current measurement results using Fuzzy logic MPPT technique: I_{out}, and I_{pv}

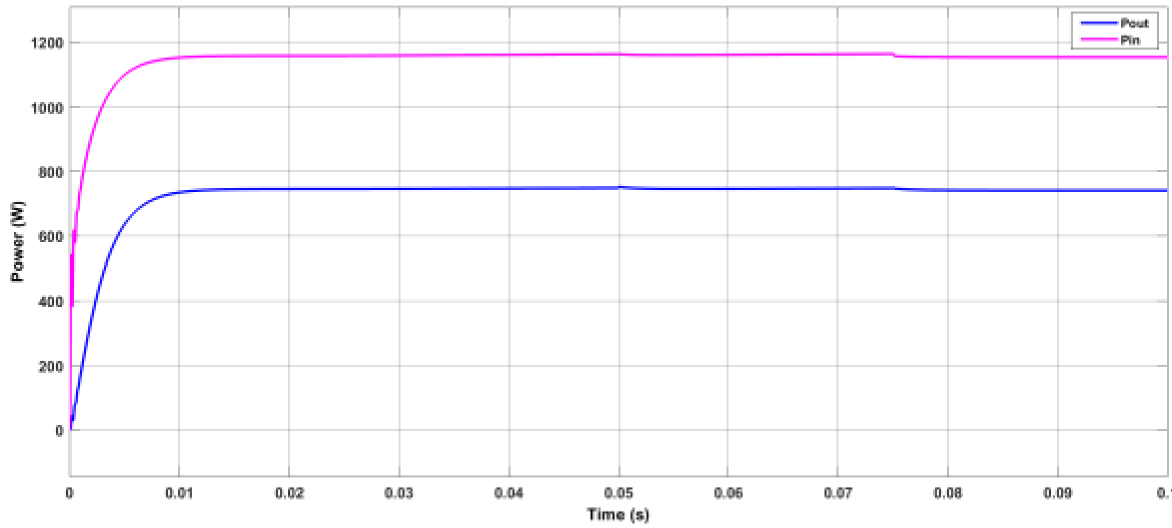

Fig. 10: The SML power measurement results using the Fuzzy logic MPPT technique under fixed solar radiation: P_{out}, and P_{pv}

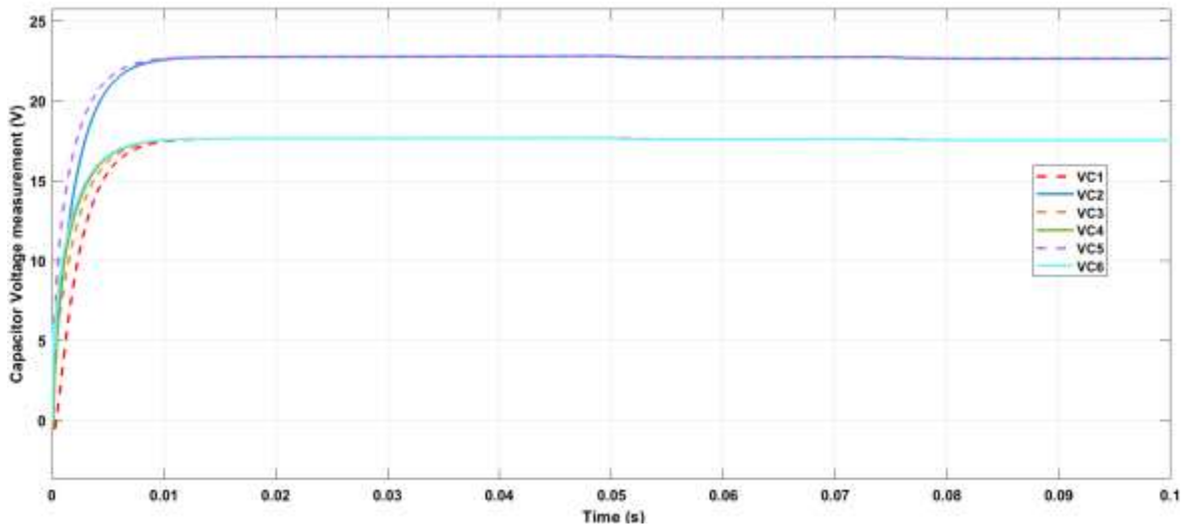

Fig. 11: The SML Capacitor voltage measurement results using Fuzzy logic MPPT technique under fixed solar radiation: $V_{C,2,3,4,5,6}$

Figure 10 illustrates the output and input power of the system. The first one reaches 745 W as the average value while the second is 1158 W which represents 96% of the PV system MPP (P_{MPPT}= 1200 W). In other words, The PV system input power is maintained at its maximum power point of 96%. However, the power loss equals 412.7 W which represents 35.66 % of the input power. Indeed, the system efficiency arrives at 64.33%. The capacitor voltage measurement of the SML converter when using the Fuzzy logic MPPT controller is given a fast response and low overshoot as shown in Figure 11. In addition, the capacitor voltage ripples are eliminated and removed using this type of controller. Since the output voltage is constituted of the input voltage and capacitor voltages sum. The enhancement of the capacitor voltage quality by removing the ripples will surely enhance the output voltage quality and efficiency. As a result, the elimination of ripples for the output signal reduces the output signal oscillations which will be highlighted in the section on solar radiation variation.

3.2 Simulation Results with Solar Radiation Variation

In this section, the solar radiation varies three times as shown in Figure 12. The first phase is during the first 0.025 s where the solar radiation equals 885 W/m^2. The second phase is from 0.025 s to 0.075 s, the solar radiation is 1005 W/m^2 and the third phase is from 0.075 s to 0.1 s, the solar radiation equals 800 W/m^2. The temperature is fixed at 50 °C.

Figure 13 illustrates the variation of the output voltage during changing the radiation. In the first phase, the output voltage is at 60 V as required. It is generated with a fast response and without oscillation at the MPPT point and with a ripple elimination feature. When passing to the second phase, the solar radiation is increased consequently the output voltage generated is boosted to the new MPPT value which is 66.46 V without oscillation or ripples. Similarly, in the third phase, when the solar radiation is decreased, the system succeeded in tracking the MPPT point with the same quality and characteristics. As a result, the output voltage is at 53 V.

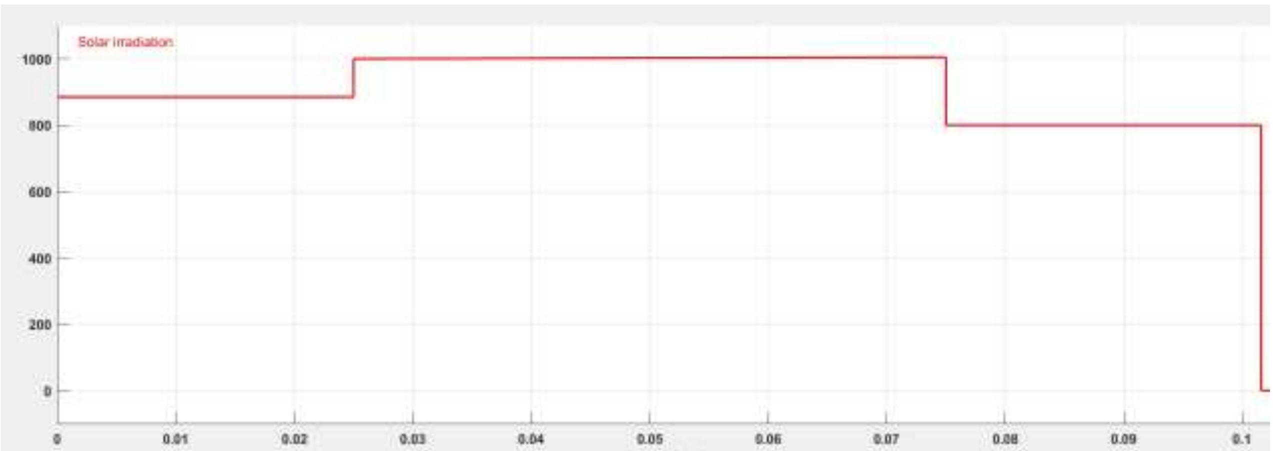

Fig. 12: Solar radiation variation of the PV panel

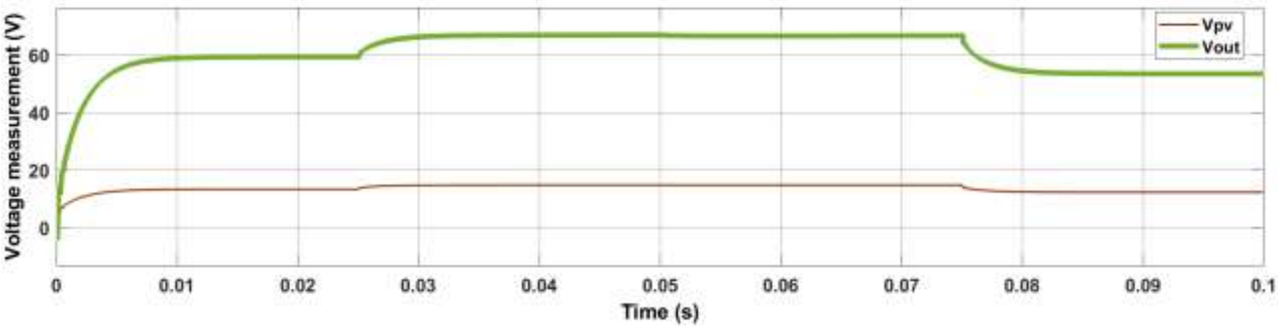

Fig. 13: The SML voltage measurement results using the Fuzzy logic MPPT technique: Under solar radiation variation: V_{out}, and V_{pv}

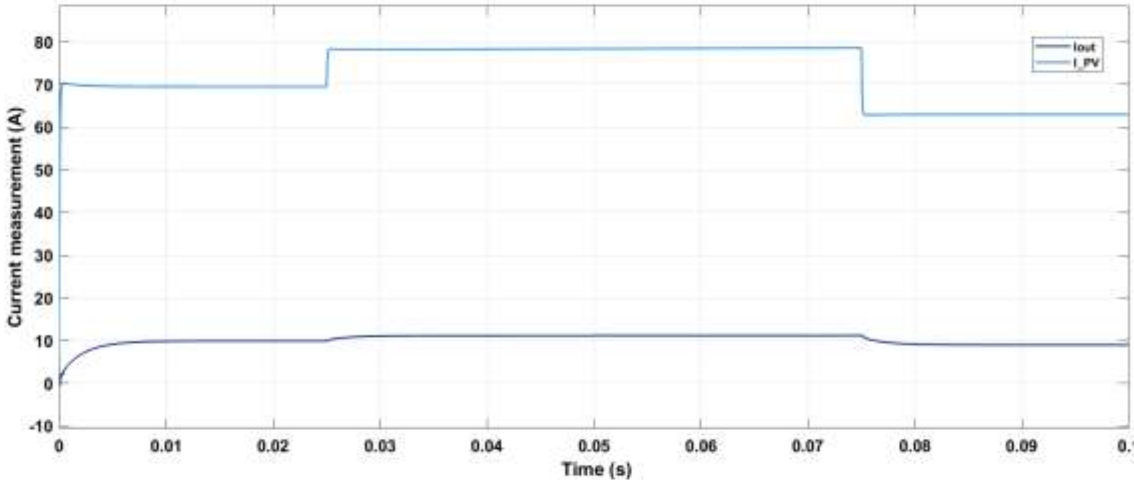

Fig. 14: The SML current measurement results using Fuzzy logic MPPT technique under solar radiation variation: I_{out}, and I_{pv}

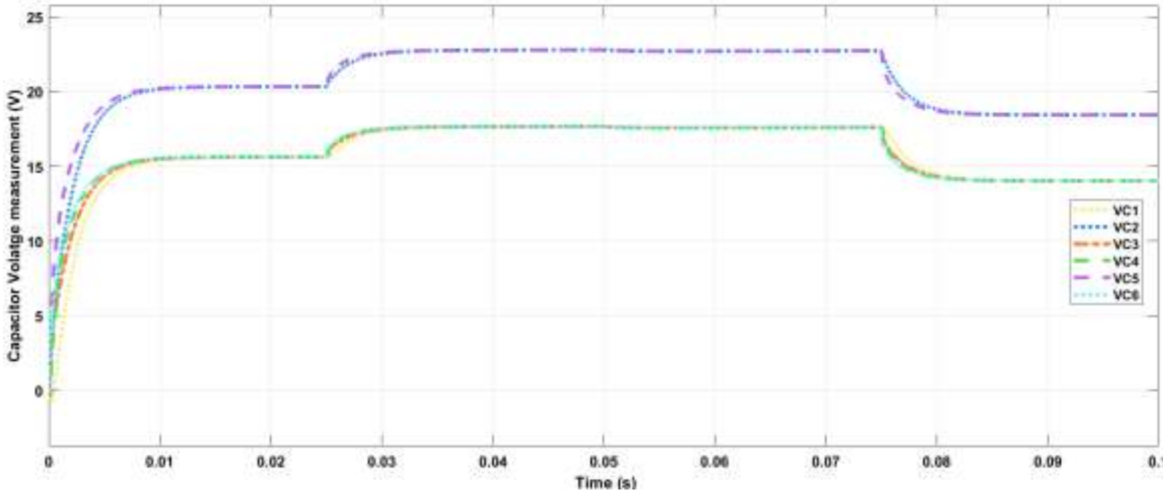

Fig. 15: The SML Capacitor voltage measurement results using Fuzzy logic MPPT technique under solar radiation variation: $V_{C,2,3,4,5,6}$

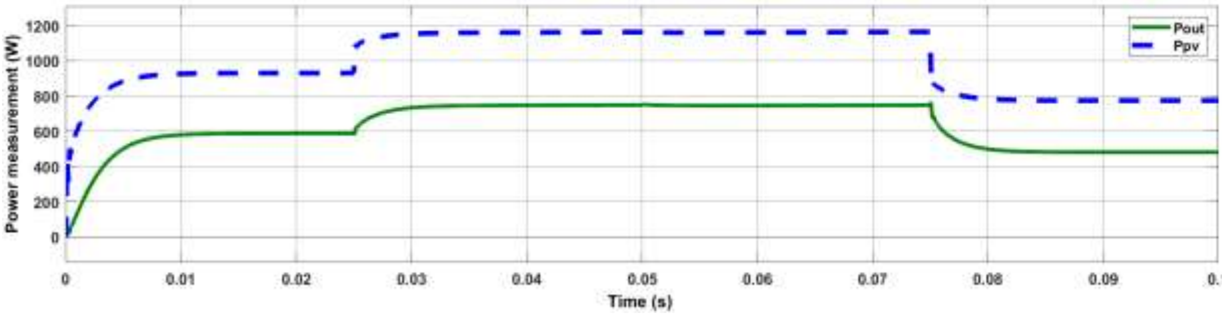

Fig. 16: The SML power measurement results using the Fuzzy logic MPPT technique under solar radiation variation: P_{out}, and P_{pv}

The six capacitor voltage measurements in addition to the output current measurement show the controller's ability to eliminate the oscillation during the transient regime and enhance the response of the output current. Indeed, according to Figure 14, the output current follows the changing of the solar radiation and the system continues to track the optimum functioning during the three phases. Similarly, the capacitor voltage oscillation and ripples are eliminated for the six capacitors as shown in Figure 15.

Figure 16 presents the SML power during the three phases of solar radiation variation. During the three phases, the system keeps tracking the maximum power points and changes its response by referring to the solar radiation change. Starting from the first

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stage, the output power is boosted from 0 W to 588 W without oscillation during the transient regime or around the maximum power point. In the same manner, during the second phase where the radiation and the power of the solar panel are changed, the output power of the system is increased to reach 741.3 W. Finally, in the third phase, the MPPT is tracked by the system to get 481.1 W as output power.

3.3 The Fuzzy Logic Adaptive MPPT Control Implementation using the PIL

3.3.1 PIL Implementation Methodology

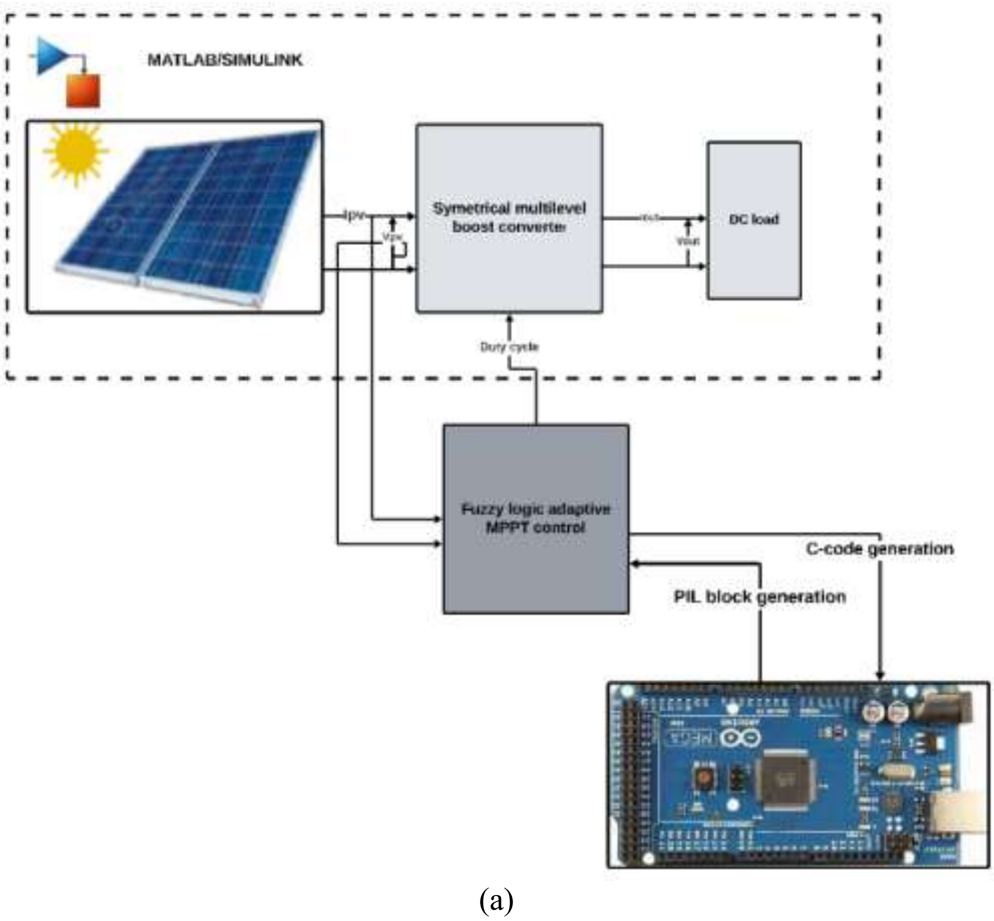
In this subsection, the testing of the fuzzy logic adaptive MPPT control in real-time with an Arduino Mega board and a low-cost co-simulation processor is implemented. The fuzzy logic adaptive MPPT control is coded in the Arduino Mega which means that the controller is tested using the Arduino board, while the solar PV, the SML, and the DC load are virtual systems built in the MATLAB/Simulink environment Figure 17 (a).

The PIL test gathers the hardware implementation for the controller and the simulation for the PV systems and converter. As a result, the applicability of the systems concerns the validation of its control using low-cost simulation. The PIL test can be configured using the Arduino Mega board using the subsequent steps:

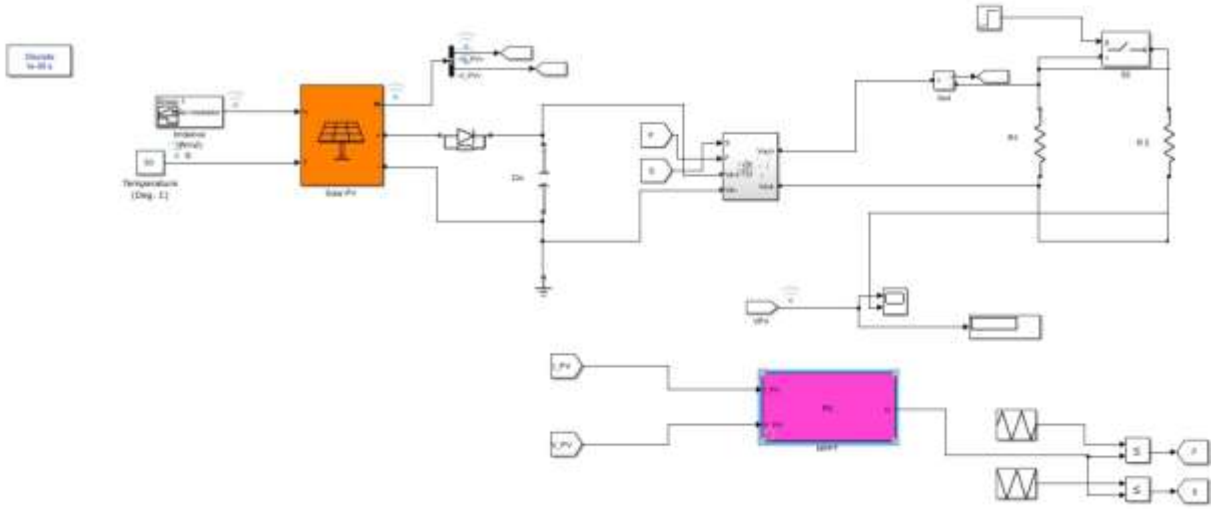
1. Open the Simulink parameters,
2. Select the hardware implementation,
3. Choose PIL as the target hardware,
4. Generate C code,
5. Build the PIL block,
6. Place the PIL block controller in the Simulink file Figure 17 (b),
7. Simulate the system.

3.3.2 PIL Implementation Results

The PIL response during constant and variable radiation demonstrates compatibility with the simulation results found in Figure 8 and Figure 13 concerning the output voltage illustrated in Figure 18 and Figure 19 respectively, which proves the effectiveness of the proposed controller.



(a)



(b)

Fig. 17: The PIL technique (a) Implementation Schematic; (b) Implementation in Matlab/Simulink

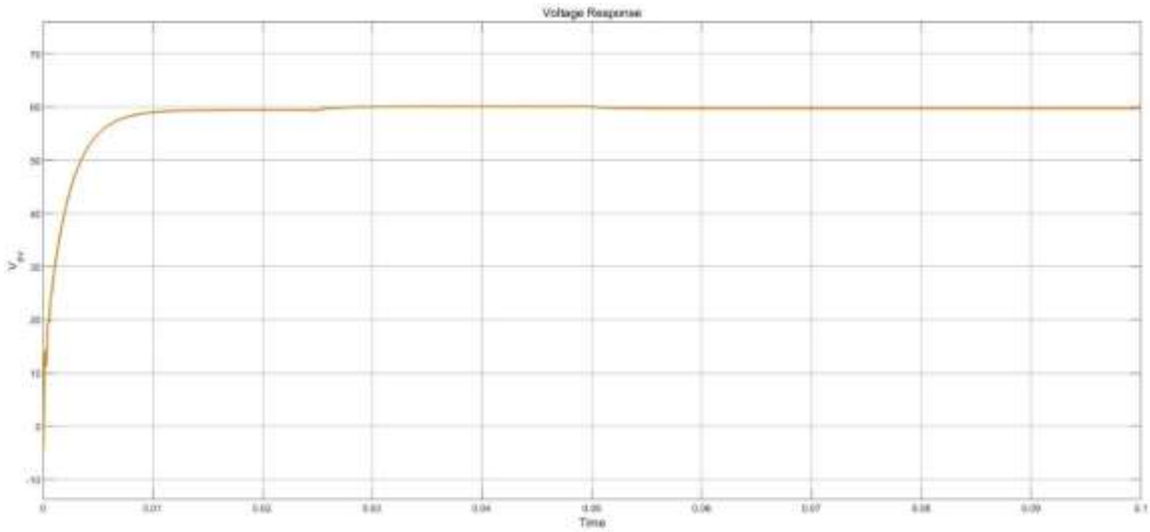


Fig.18: Output voltage using the PIL co-simulation during fixed radiation

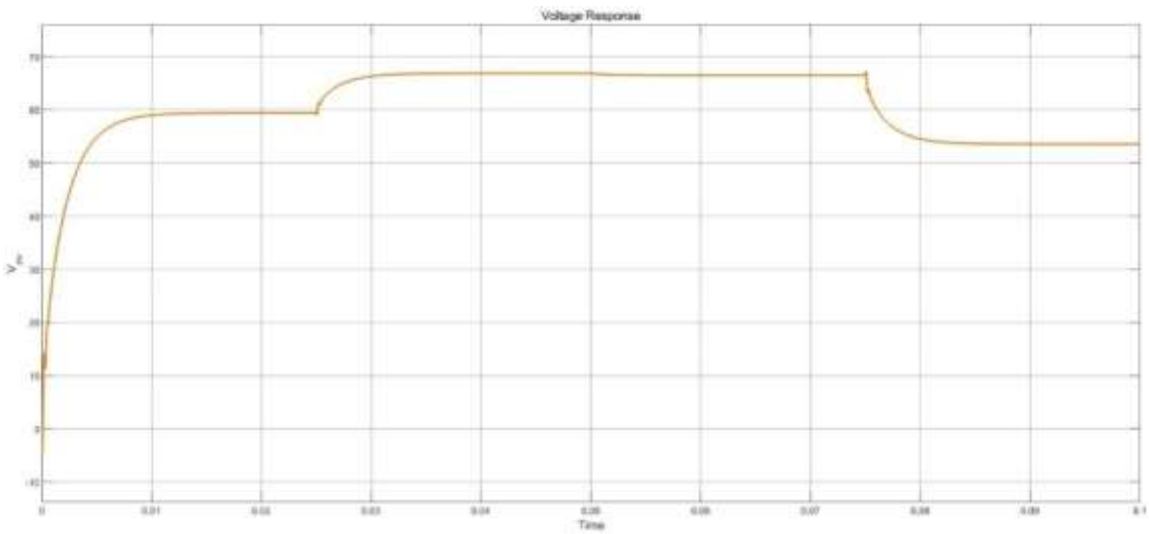


Fig.19: Output voltage using the PIL co-simulation during variable radiation

4 Conclusion

In this paper, the fuzzy logic adaptive MPPT controller has been designed and implemented for a symmetrical multilevel boost converter in a Standalone PV system. The controller is implemented in Arduino Mega board to test its efficiency. Results prove that the fuzzy-based MPPT controller can adjust the PV generator power to meet its maximum power functioning with 96% during the two tests: fixed solar irradiation and variable solar irradiation without perturbation and oscillation in the maximum power point, for simulation in Matlab/Simulink. In addition, the controller applicability using the Arduino Mega via the processor in loop test validates the simulation results. From a perspective, the full hardware implementation of the system is highly recommended.

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