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Design and Experimentation of a Control System Implemented on Raspberry Pi 3 Board for Photovoltaic Systems Using SEPIC Converter

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In this paper, a voltage regulation system is proposed for photovoltaic energy sources (PV), using Single-Ended Primary Inductance Converter as a DC-DC converter to feed loads working with specific input voltage. The choose of SEPIC converter is due to the output voltage ripple of developed-type converters are usually small and can be lower than 2%, also it considered as a buck and boost converter and thereafter loads with lower or higher voltage could be powered. Matlab Simulink is used as environment to develop control strategies to guaranties a stable voltage at the loads terminals. Two algorithms are used to fulfill this role: A Conventional PID and PI-Fuzzy logic controller to generate the PWM signal for the SEPIC converter. Hence, to validate the work some real-time simulations are treated by implemented the control strategies on a low-cost control board: The Raspberry Pi 3 in order to manage the operation of system and collecting the simulation data. Also, and for verification purposes, several simulations were treated to verify the good behavior of the proposed system.

Keywords: Voltage control system, Photovoltaic system, DC DC power converters, SEPIC Converter, Raspberry Pi 3 Board, PID controller, PI Fuzzy logic controller.

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1. Introduction

In recent decades, the use of renewable energy has gained importance in many applications, then an interest of researchers appeared to optimize and exploit the use of this resource.

Photovoltaics in turn is among the most remarkable sources that transforms the light radiation into electricity, but what makes the recovery of energy not easy is that the photovoltaic energy production depends directly of serval parameters, namely temperature and level of irradiation. Hence an unstable voltage at its terminals.

In the case where we need to supply loads with stable voltage well defined to ensure their operation [1], it is necessary to do what we call controlled voltage system which this is the aim of our work. The controlled voltage system must guarantee a constant voltage in the terminals of the load even if there is a change of load, change of voltage supply of the photovoltaic source.

DC-DC converters, a power electronic circuit, are used for voltage adaptation between photovoltaic source and loads. This kind of static converter are used due to low loss power, high efficiency as well its used in many industry applications.

Multiples generation of DC-DC converter has been developed over the years, on where we can find the step-up input voltage also called boost, step down input voltage the buck converter, and the buck-boost converter to get lower or higher voltage depending of the need.

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In this paper a special type of DC-DC converter Buck-Boost converter, type Single-Ended Primary Inductance Converter (SEPIC), has been proposed to control transmitted power from photovoltaic source and loads [2]. This type of conversion is handy when the designer uses voltages from an unregulated input power supply.

However, to control the load voltage even with unregulated input voltage, the electronic switch should be controlled periodically by a PWM signal, adjusting the On and Off times to get the adequate duty cycle hence the desired output voltage.

In this paper, a real-time simulation with the proposed system has been developed using two control strategies such as conventional PID and Fuzzy control system, implemented on a Raspberry Pi 3 board [3]. The simulation results given at the end of the paper, are recovered ad displayed on Matlab Simulink to validate the work.

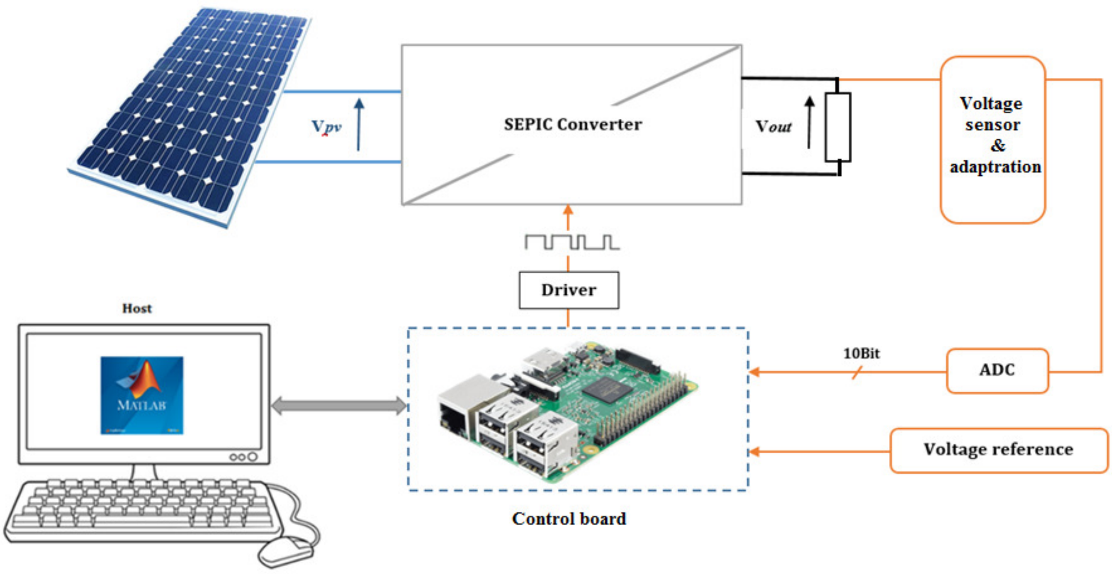

Figure 1. Topology of the proposed system.

Figure 1. represents the general block diagram of the studied system, containing:

- The photovoltaic panel (voltage Source).
- A DC-DC converter, type SEPIC.
- Voltage sensor and voltage adaptation block.
- An ADC converter.
- Raspberry Pi 3, as control board.
- The host (computer with Matlab Simulator).

2. The SEPIC converter circuit:

Basic converters are used to provide only steps down input voltage, case of buck converter, or steps up input voltage case of boost converter. But for many applications where we need to both step up and step down, depending on the input and desired output voltage. The Single-Ended Primary Inductance Converter (SEPIC) presents a good solution for those kind of application, and has become popular in recent years in battery powered systems that's must step up or down depending upon the charge level of the battery [2][4].

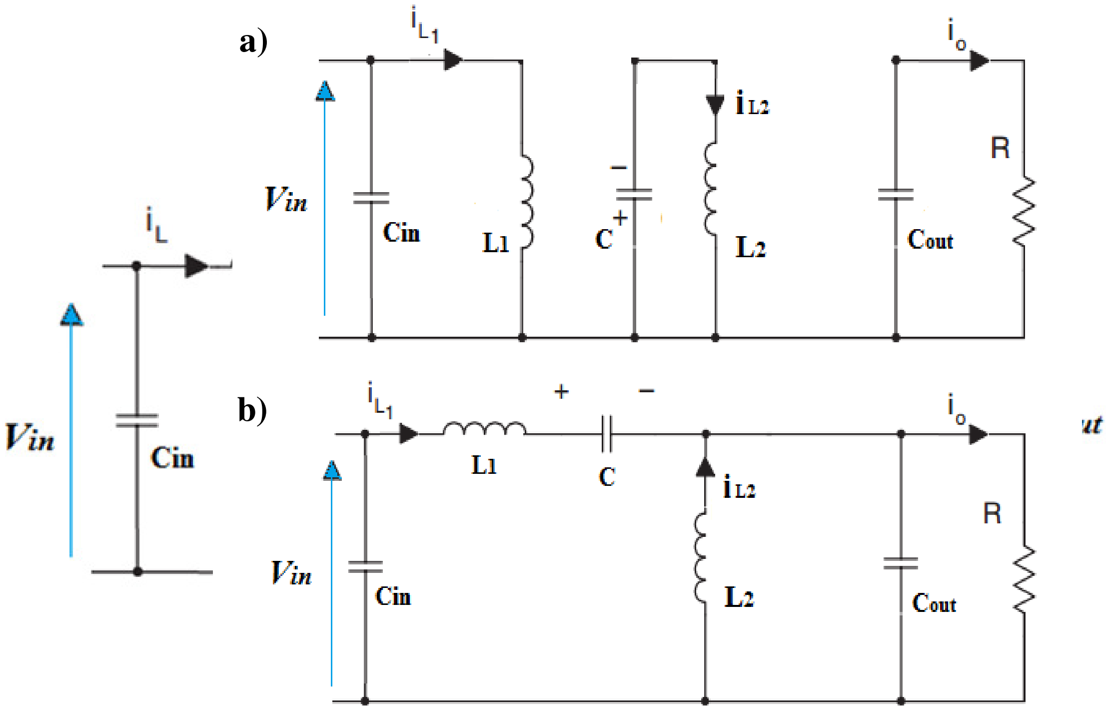

Figure 3. Switching on (a) and off (b) circuit, respectively

Figure 2 shows the circuit of the SEPIC. When the power switch K is turned on, as shown in Figure 3/a, the first inductor L_1 is charged from the input voltage source during this time. The second inductor L_2 takes energy from the capacitor C, and the output capacitor is left to provide the load current.

When the power switch K is turned off, the first inductor charges the capacitor C and provides current to the load, as shown in Figure 3/b. The second inductor is also connected to the load during this time, hence both inductors provide current to the load and output capacitor.

The input capacitor C_{in} is added to filter the variations of the input voltage and a Schottky diode is used to minimize loss power in the converter by dint of it low forward voltage drops and fast switching action.

Conidering the forward voltage drop of the Schottky diode negligible, the equations describing the relationship between the input and output voltage can be rewritten as:

$$\frac{V_{out}}{V_{in}} = \frac{\alpha}{1-\alpha} \tag{1}$$

With $\alpha = t_{ON}/T$ is the duty cycle of the PWM signal, which represent the control signal.

A duty cycle close to 50%, The input voltage is equal to the output voltage, the gain is unitary.

One of the first steps in designing any PWM switching regulator is to decide how much inductor ripple current, Δ_{IL}, to allow. Hence its necessary to size electrical components, inductors and capacities to avoid working in DCM (discontinuous conduction mode).

Generally, a ripple margin of 20% to 40% of the maximum input current is allowed for the minimum input voltage. The current ripple is defined by the following equation:

$$\Delta I_L = I_{in} \times 30\% = I_{out} \times \frac{V_{out}}{V_{in(\min)}} \times 30\% \tag{2}$$

Thus, the duty cycle varies as a function of the input voltage, it is maximal when the input voltage is minimal $V_{in(\min)}$:

$$\alpha_{\max} = \frac{V_{out}}{V_{in(\min)} + V_{out}} \tag{3}$$

The expressions of the minimum inductances to be chosen, is given in the form:

$$L_{1(\min)} = L_{2(\min)} = \frac{1}{2} \times \frac{V_{in(\min)} \times \alpha_{(\max)}}{\Delta I_L \times f_{sw(\min)}} \tag{4}$$

With: $f_{sw(\min)}$ the minimum switching frequency.

For the coupling capacitor C, must be able to pass the RMS current given by:

$$I_{C(RMS)} = I_{out} \times \sqrt{\frac{V_{out}}{V_{in(\min)}}} \tag{5}$$

The capacitor value is sizing for the desired maximum ripple voltage, defined by the formula:

$$\Delta V_C = \frac{I_{out} \times \alpha_{\max}}{C \times f_{sw}} \tag{6}$$

For the output capacitor C_{out} , which filter the output voltage of the SEPIC converter. The expression of capacitor dimensioning is given by:

$$C_{out} \geq \frac{I_{out} \times \alpha_{\max}}{V_{ripp} \times f_{sw(\min)}} \tag{7}$$

V_{ripp} : represent the output ripple voltage.

3. Conventional PID and PI-Fuzzy controllers:

For the control system, two control strategies have been used to generate the adequate PWM with a specific duty cycle to control the electronic switch, so as to get the desired output voltage [5-6].

The idea of the control system is to compare the output voltage with the desired one, called the set point, in order to minimize the error between them, by the intervention on the duty cycle of the electronic switch with an analog response signal which must be converted on a PWM signal -by means of a comparator block as shown in Figure 4.

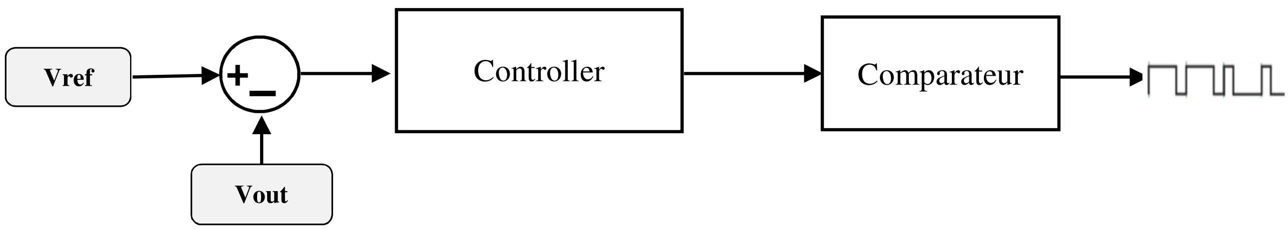

Figure 4. Controller system

3.1. PID controller:

Conventional Proportional, Integral and derivate controllers are the best-known controllers used in many industrial processes due to its simplicity and robust performance. But the use of this kind of controllers has a limitation when the linearization of the system, we want to control, becomes delicate or impossible. And this is the case of the DC-DC converters.

3.2. PI Fuzzy Logic Controller design:

For the second control strategy, the fuzzy logic, a relevant strategy which was introduced in 1965 by Lofti A Zadeh in his paper "Fuzzy Sets". During the past several years, fuzzy control has occurred as one of the most active and fruitful research areas.

Fuzzy logic controllers are designed particularly for nonlinear dynamic systems with many inputs and outputs which can be so complex, difficult to impossible to build exact mathematical model. while, no mathematical modeling of the system is required to design controller parameters, it is simple to design, cost effective, especially when it provides a hint of human intelligence to the controller.

Fuzzy logic allows reasoning, not on numeric variables, but on linguistic variables, i.e., on qualitative variables (*large, small, medium, far, near, etc.)*. The fact of reasoning about these linguistic variables will allow manipulating knowledge in natural language.
As shown in figure 5, the fuzzy logic controller block is divided into 3 steps: the Fuzzification, the Fuzzy inference engine and the defuzzification.

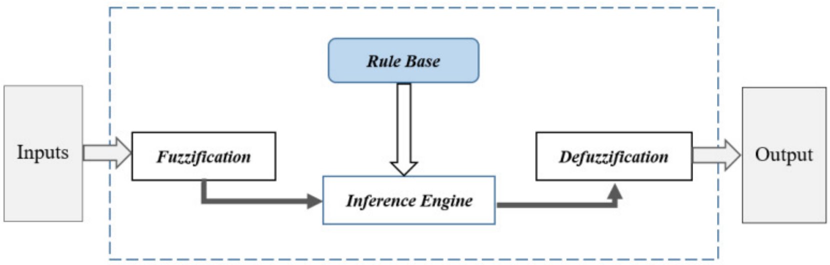

Figure 5. Fuzzy logic controller sub-blocks

The purpose of the first step 'Fuzzification' in the fuzzy inferencing process step is to transform actual magnitudes linguistic variables. This involves a domain transformation where crisp inputs are transformed into fuzzy inputs. Crisp inputs are exact inputs measured by voltage sensors in our case and passed into the control system for processing.

In this paper, a PI-Fuzzy logic controller has been proposed, which contains two inputs variables: the voltage error and the variation of error.

$$\varepsilon = V_{ref} - V_{out}$$
$$\Delta\varepsilon = \varepsilon(t) - \varepsilon(t-1) \tag{8}$$

Membership functions, as shown in Figure 6, are used in the fuzzification and defuzzification steps of a Fuzzy logic system, to map the non-fuzzy input values to fuzzy

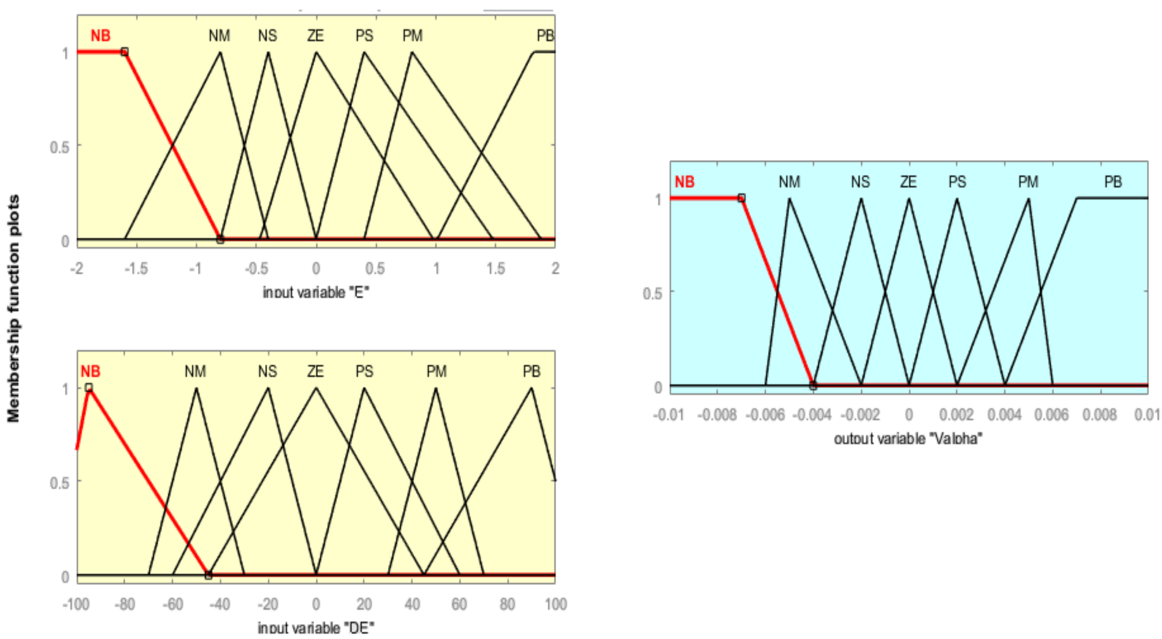

Figure 6. Inputs and output membership function

linguistic terms and vice versa.

For the output called $\mathbf{V_{alpha}}$, is considerate as the variation of the response necessary to do to increment or decrement the duty cycle.

Seven memberships functions, for each input and output, have been used to get better variables representations [7-8].

Afterwards, an inference is made based on a set of rules which is constructed to control the output variable. A fuzzy rule is a simple IF-THEN rule with a condition and a conclusion. It collects various combinations between the two inputs to generate the appropriate duty cycle change value. These rules are represented in table 1.

Table 1. Fuzzy rules.

DE	**E**						
	NB	***NM***	***NS***	***ZE***	***PS***	***PM***	***PB***
NB	*ZE*	*ZE*	*ZE*	*PS*	*PM*	*PB*	*PB*
NM	*NS*	*ZE*	*ZE*	*PS*	*PM*	*PB*	*PB*
NS	*NM*	*NS*	*NS*	*ZE*	*PS*	*PM*	*PB*
ZE	*NB*	*NM*	*NS*	*ZE*	*PS*	*PS*	*PB*
PS	*NB*	*NM*	*NS*	*NS*	*ZE*	*PS*	*PM*
PM	*NB*	*NB*	*NM*	*NS*	*PS*	*ZE*	*PM*
PB	*NB*	*NB*	*NB*	*NB*	*PS*	*ZE*	*ZE*

After inference step, the response should be converted in a crisp output by the way of the defuzzification bloc. Several defuzzification methods can be used such as center of gravity which is the most used method.

4. Simulation results under Matlab Simulink:

Figure 7, shows the proposed system implemented on Matlab Simulink. Dimensioning components and controllers' parameters are done in table 2 and 3.

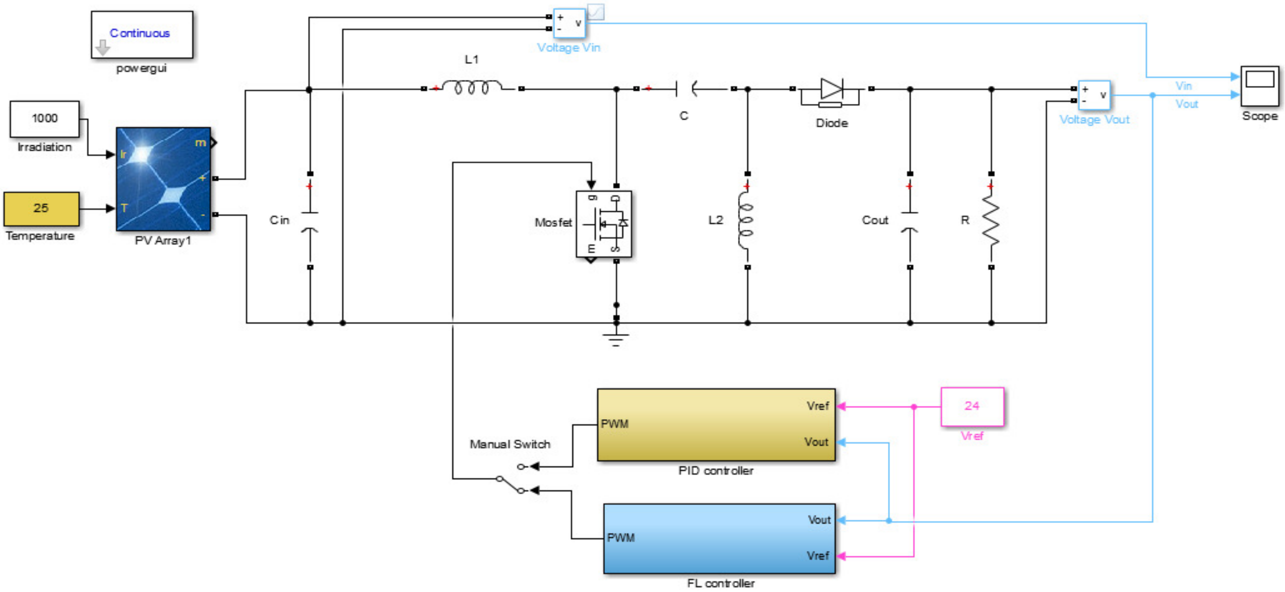

Figure 7. System blocks under Matlab Simulink

Table 2 SEPIC sizing components

Component	Value / Type	Component	Value / Type
C_{in}	470uF	L2	2 mH
L_1	2 mH	Schottky diode forward voltage drop	0.3V
Switch K	MOSFET	C_{out}	2200uF
C	470uF	Load (Initial value)	150Ω

Table 3 Controllers parameters

Control strategy	Parameters values
Conventional PID	K_p=0.03; K_I=0.5; K_d=0.001.
PI-Fuzzy logic	K_p =1/26; K_I =15

Simulations results ae shown in part to validate the good behavior of the system, using Matlab Simulink as environment, in cases of input voltage change (irradiation change case for photovoltaics sources), load change and reference change.

4.1. Reference voltage change:

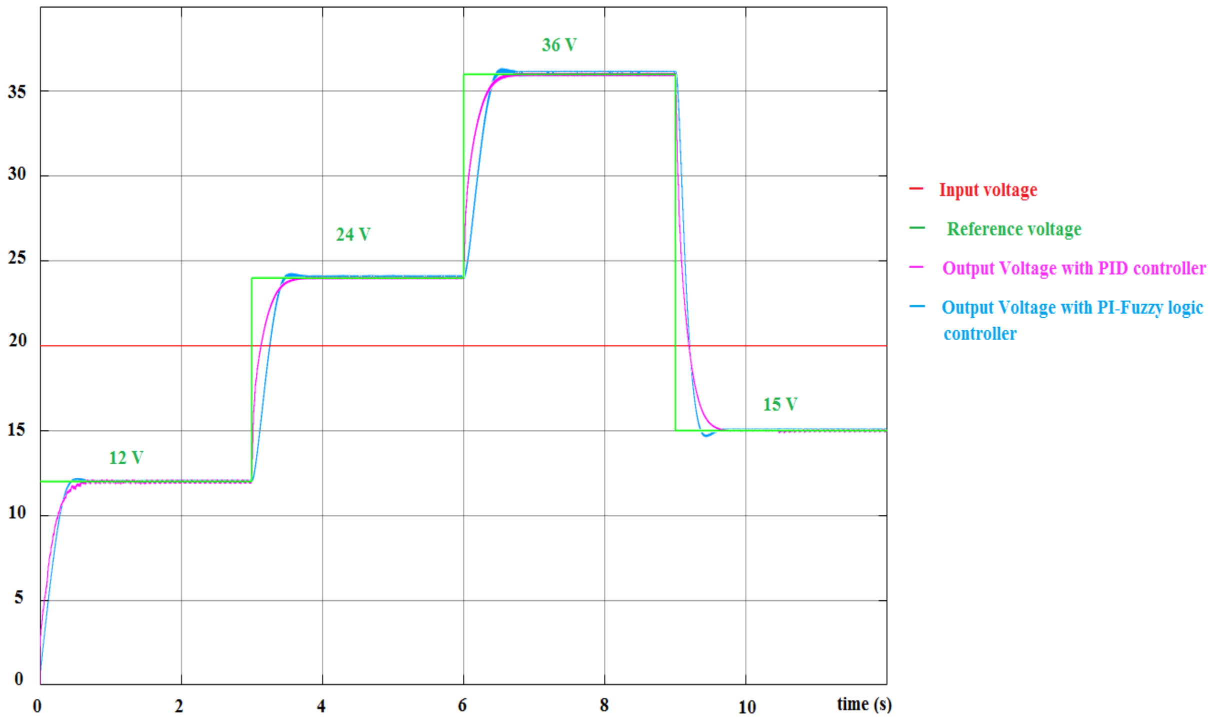

Figure 8. Voltage reference change case

In this case, input voltage is fixed to 20V. Reference voltage (Set point) is not constant under times, then as shown in figure 8, the output voltage pursuit exactly the reference with different values of this latter, with both control methods.

From figure, the rising time to achieve the voltage reference is 0.7s for the PI-fuzzy logic controller and 0.85s for the conventional PID controller.

4.2. Input voltage change:

As already mentioned, photovoltaic power production depends on many parameters such as level of irradiation, hence the voltage at its terminals is not regular.

Second simulation under Matlab Simulink, take in consideration this case by changing the input voltage during system operation.

First, the input voltage is fixed to 20V, then at t=4s, it increases to 24V. In this moment, the proposed system tries to correct this variation, by changing the response duty cycle. And next, the transferred power from the input to the load.

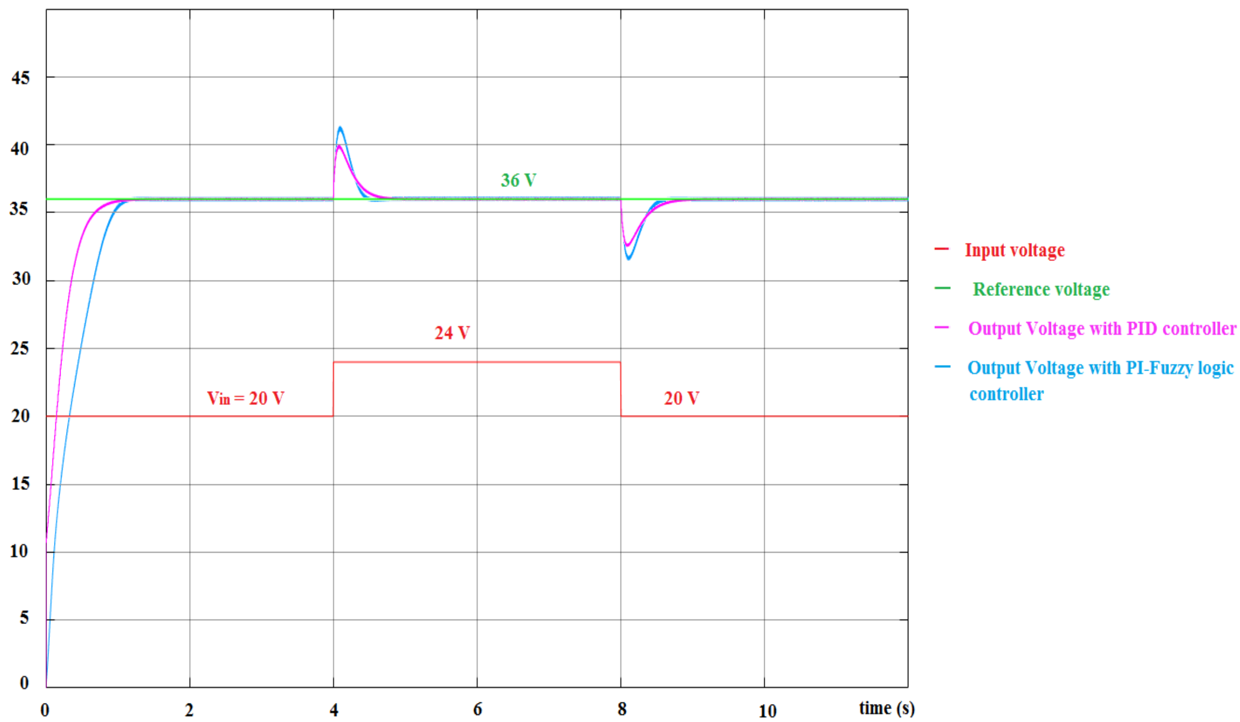

Figure 9. Input voltage change simulation case

4.3. Load change case:

Last simulation takes the cases of a change in the load. For this simulation, the initial load value is 50Ω, then at t=4s it changes to 40 Ω. And after 2s it return to 50Ω.

Figure 10, shows the system response using both control strategies. The output voltage pursuit the fixed reference voltage quickly.

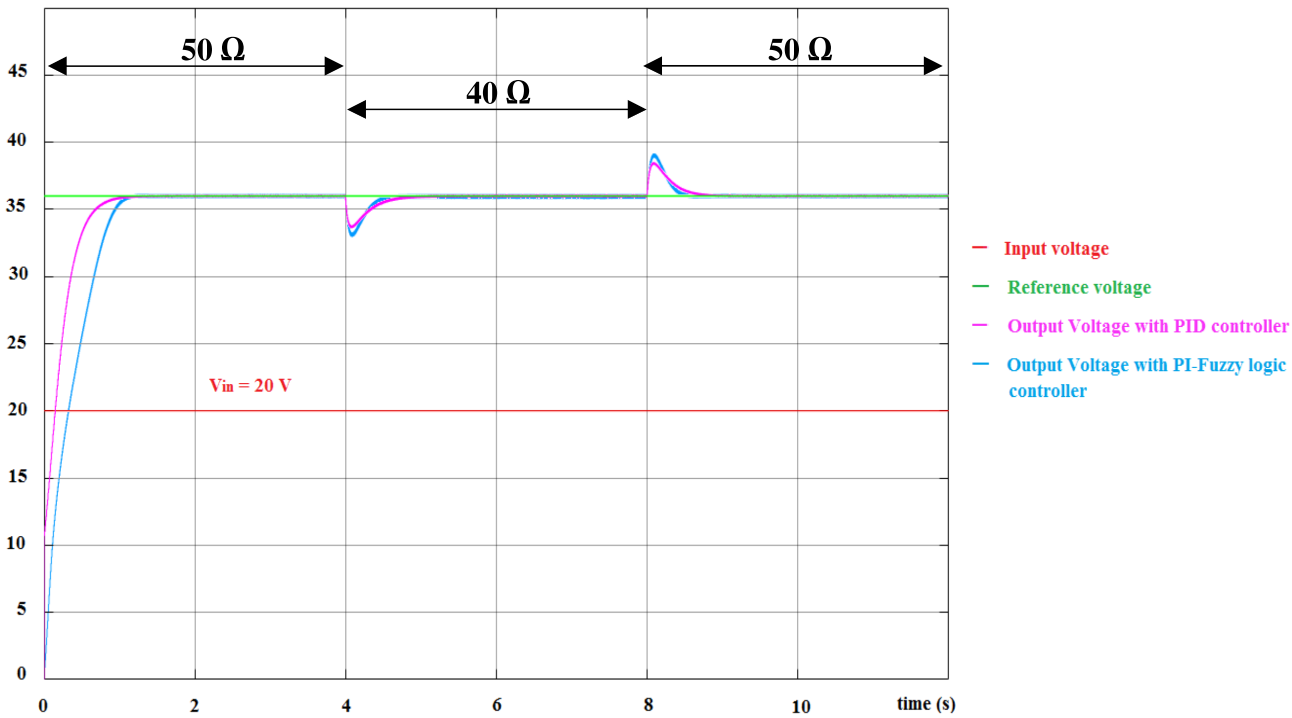

Figure 10. load change case

5. Implementation and real-time simulations:

After simulation on Matlab Simulink, some experimental tests were done to validate the good behavior of the proposed system.

For the input source, photovoltaic source was replaced by a DC voltage supply.

Per figure 1, controllers will be implemented on a control board; it is the main function of the Raspberry Pi 3 (Figure 3), in order to make real time control and simulation [9-12].

The Raspberry Pi 3 is the third-generation Raspberry Pi. One of the powerful control board on the market, with a reasonable price.

A Raspberry Pi 3 model B board is used in this work, (Figure. 11) for the implementation of the Simulink controller block and data acquisition.

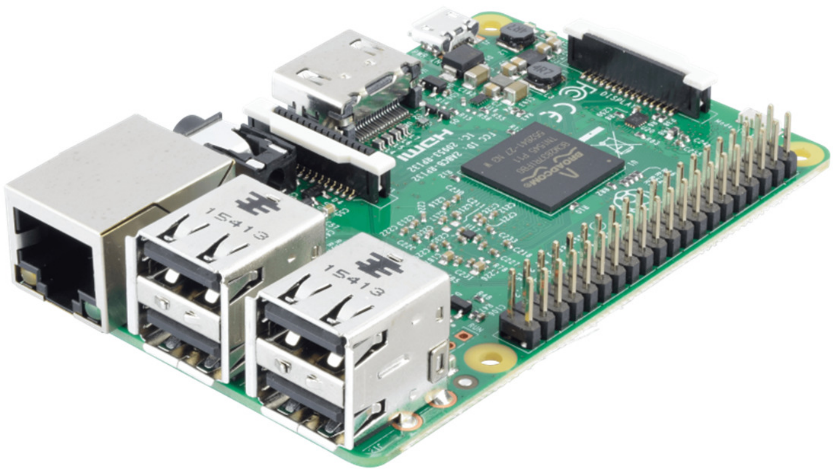

Figure 11. Raspberry Pi 3 64-bit microcontroller board

The choose of this king of boards amounts to multiples advantages of ease of use, direct communication with a multi development environment as Matlab Simulink.

Due its performance, the Raspberry can run quite heavy programs without problems, circulates and processes the information quickly by dint of the high operating frequency of 1.2GHz and the RAM size that reaches 1GB as shown in Table 4.

Raspberry is an open-source electronics platform based on easy-to-use hardware and software. The Raspberry Pi 3 model B is a microcontroller board based on the 64-bit quad-core ARM Cortex-A53, 1.2GHz processor, with 512kB shared L2 cache, supports all the latest ARM GNU/LINUX.

The control board has also an integrated Bluetooth and Wi-Fi, for wireless communication.

Table 4. Characteristics map of Raspberry Pi 3.

CPU	64-bit quad-core ARM v8 Broadcom BCM2837
Clock frequency	1.2GHz
RAM	1GB
USB port	4
Ethernet port. RJ45	1
HDMI	1
GIPO Header	40 pins
GIPO voltage	5V
Power limit	700mA

5.1. Implemented system description:

As shown before, in figure 1, to control the output voltage and making it near to it reference, a portion of this output signal must be read via a voltage sensor and adaptation block.

The use of the adaptation block is to limit the reading voltage from the voltage sensor to the GIPO inputs.

The adaptation block which were used, as shown in figure 12, is based on an instrumentation amplifier in order to eliminate the effect of the input impedance of the circuits which follows and then read the output voltage reliably, and without forgetting to protect next blocs inputs in case of exceeding the operating limit voltage.

V_{out}'' represents the image of the DC DC converter output voltage.

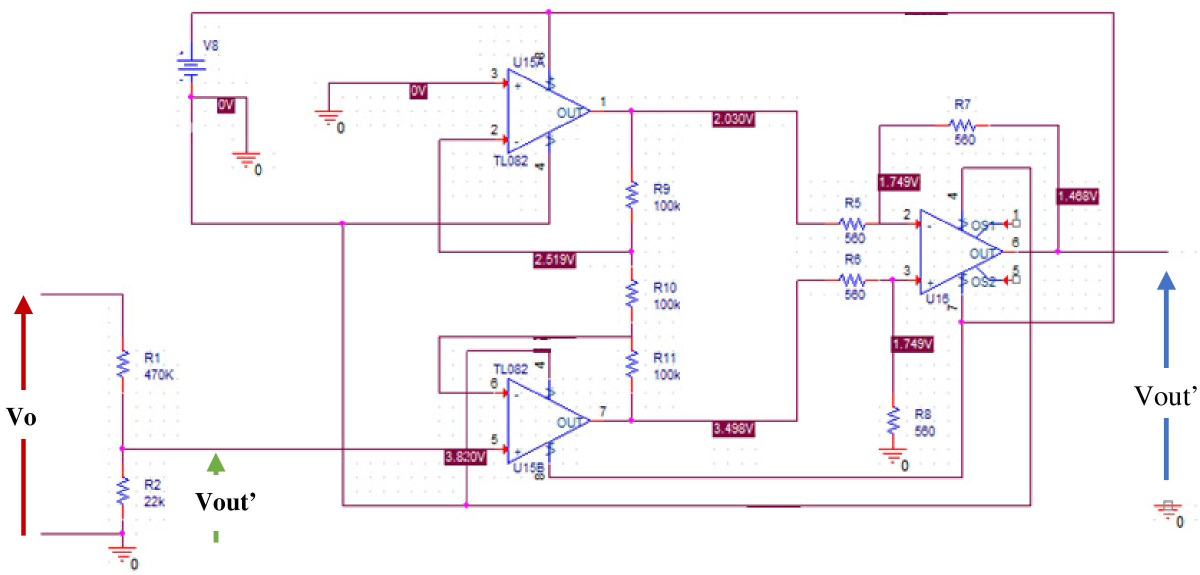

Figure 12. Adaptation block and voltage sensor.

Since the output voltage is an analogic signal and Raspberry boards don't contain an analog input, using an external ADC converter is indispensable.

A 10-bit ADC converter is used with a resolution of 4.88mV, in a scale of 0-5V.

$$resolution = {}^{5V}\!\big/_{2^{10}} = 4.88\,\mathrm{mV} \tag{9}$$

Figure 13, shows the block diagram of the integrted controllers strategies, conventional PID and the PI-Fuzzy logic controller, modleing on Matlab Simulink and implemented on the control board.

Received data from the GIPO pins should be converted to an analog signal before treatment.

Afterward it is compared to the set point reference voltage, by calculating the voltage error. Controller block comes after to generate the adequate response in order to minimize this error.

A comparator block comes after to convert the response value from the controller to a PWM signal in order to control the electronic switch (MOSFET) of the SEPIC converter.

The generated PWM signal is sent to the GPIO output at Pin 18 of the Raspberry Board.

All data are collected and transmit to the host (Computer), which is used to acquire and plot the output voltage signal in real time simulation.

Controllers parameters are done in Table 3.

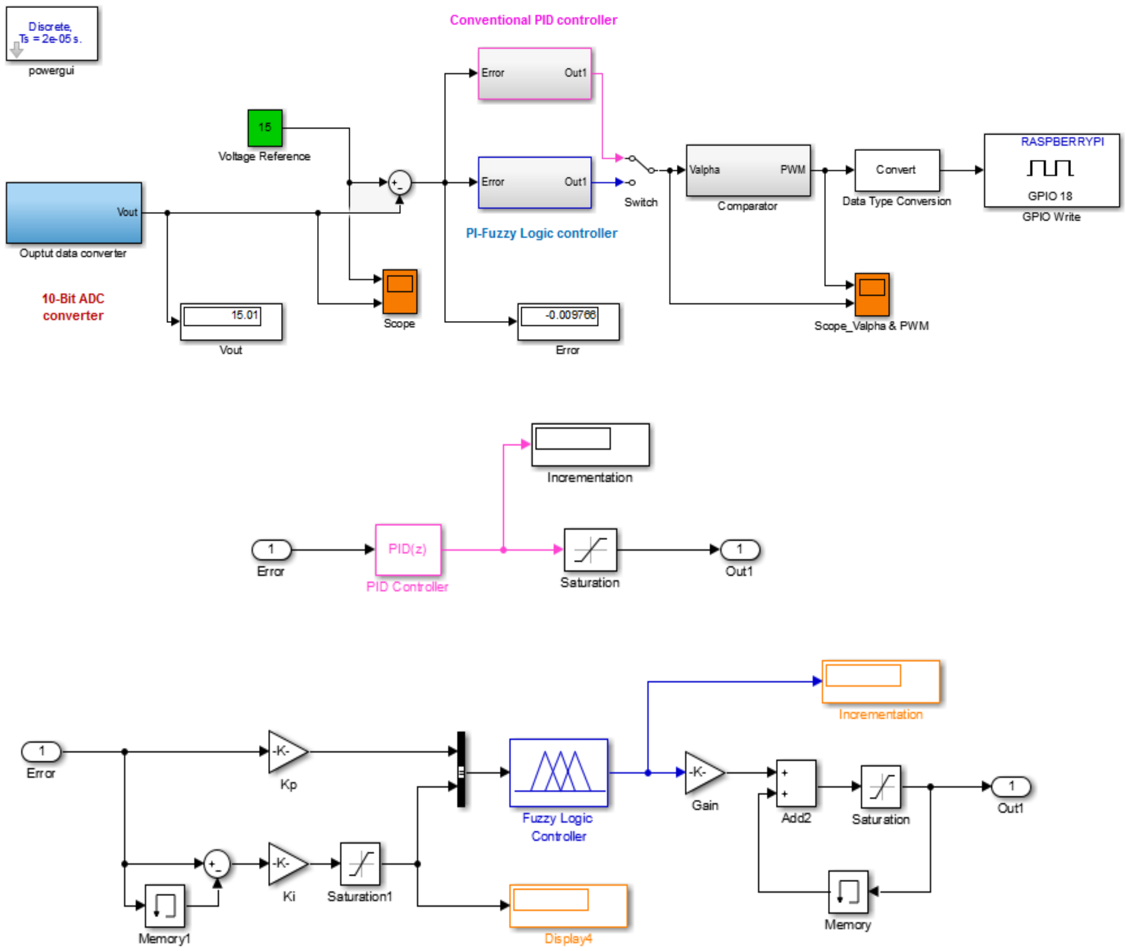

Figure 13. Block diagram of the implemented

5.2. Experimental test and results interpretation:

Figure 14 shows the experimental hardware setup of the proposed system.

A real-time simulation was launched to verify the good behavior of the proposed system using both control strategies.

Serval tests are done in case of source voltage change, a continued change of the set point and load change case.

For all test, as fixed parameters, the supply voltage input is set to $V_{in} = 7.5V$. In extended work, it can be replaced by a photovoltaic source.

The load is chosen as resistif having as initial value $R_{ch} = 150\Omega$.

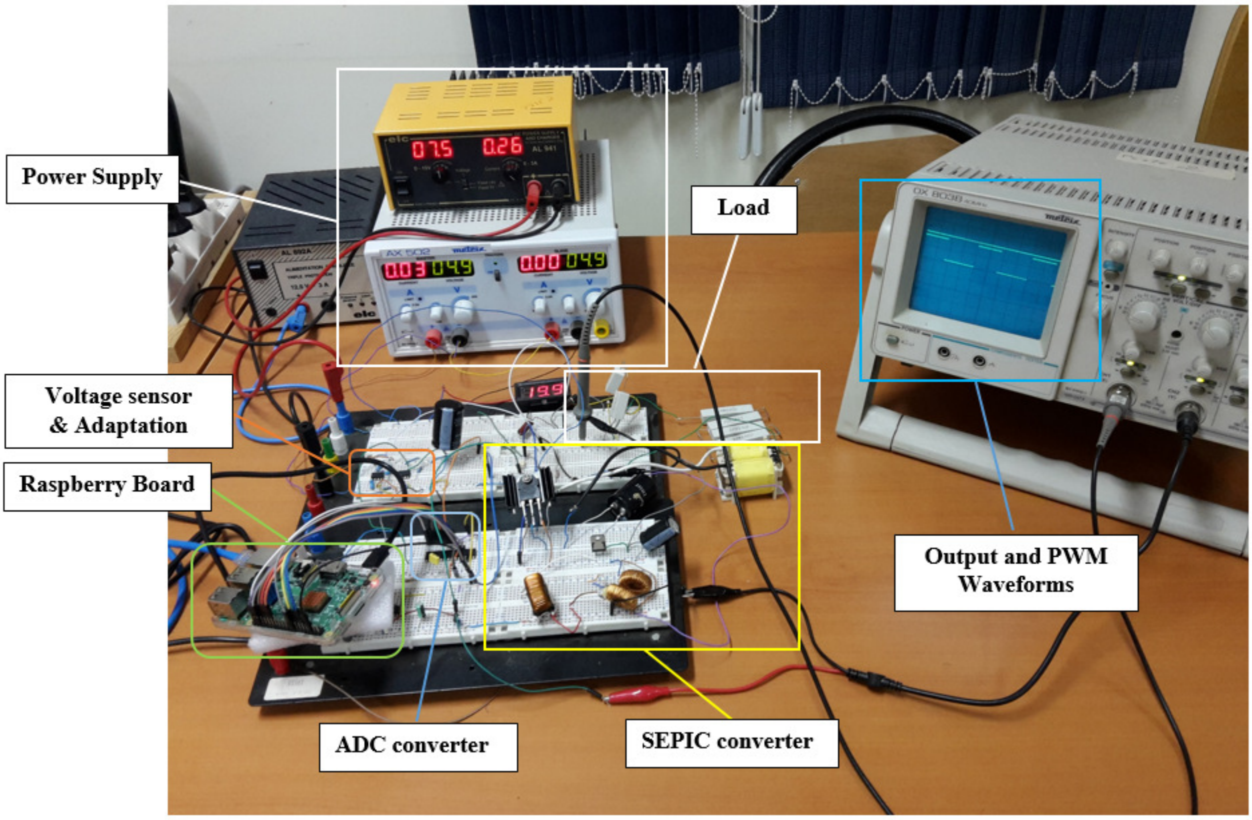

Figure 14. The experimental hardware setup.

5.3. Set point change pursuit:

In the first simulation test, the input voltage is set to 7.5V, load to 150Ω.

Reference voltage is considered as variable in time, as shown in Figure 15.

From figure, any change on the reference voltage begets a correction of the calculated error, hence a quick pursuit of the output signal.

Pink plot represents the output voltage response using conventional PID controller, and the blue one with the PI-Fuzzy logic controller.

Per the Figure, both controllers give good pursuit with a reduced rise time, about 0.5s for the passage from 0 to 15V.

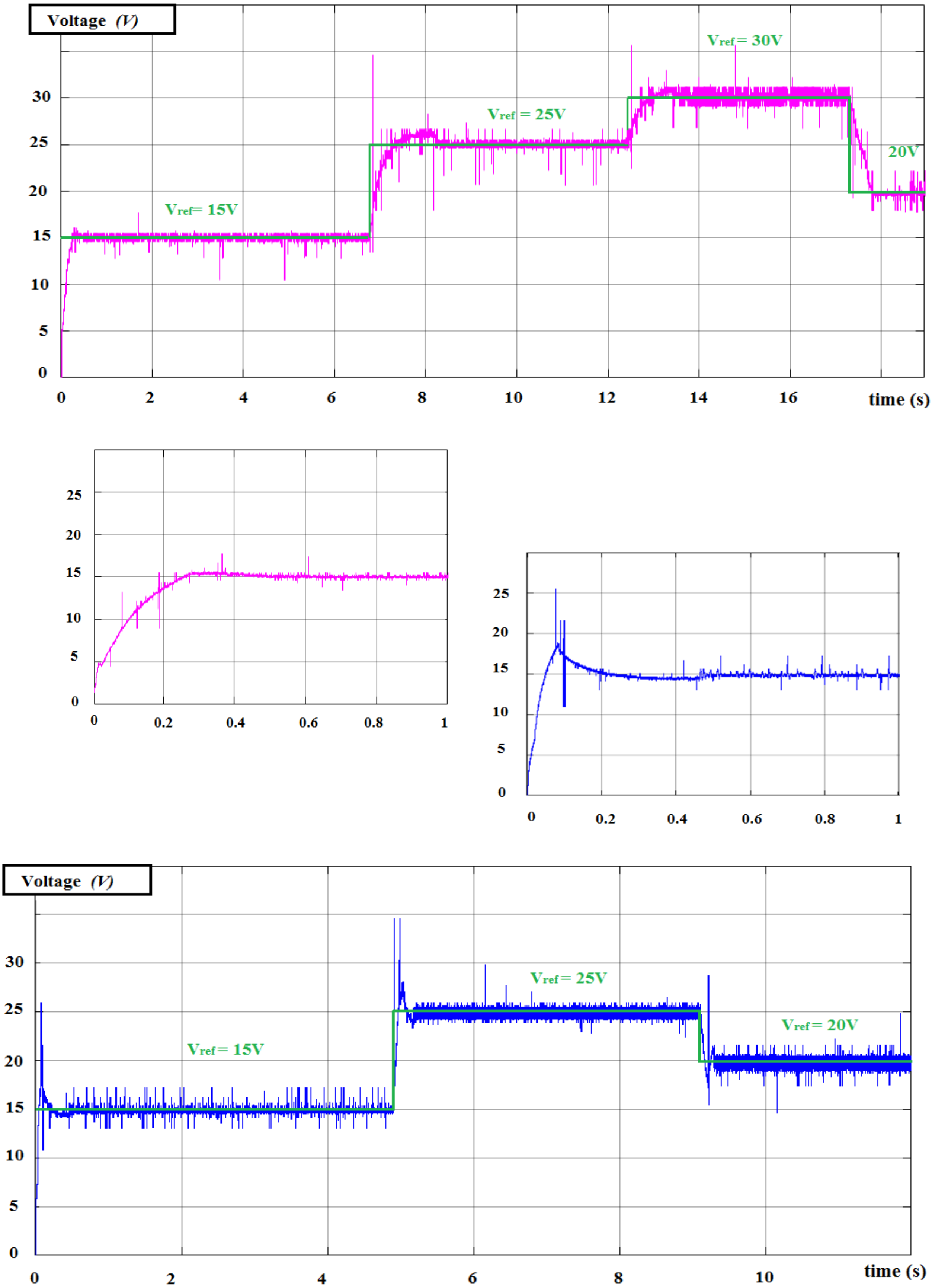

Figure 15. Reference pursuit using PID (Pink signal) and PI-Fuzzy logic Controllers (blue signal)

5.4. Voltage input change pursuit case:

In practice, the power supply is a photovoltaic source. A source on which the produced energy can change depending on the level of irradiation and temperature.

For this simulation, a no regular voltage supply is taken to improve the pursuit of the reference even with a change off those parameters.

Voltage input has as initial value 7.5V and it drops to 9V then to 7V.

Figure 16, shows the evolution of the output signal V_{out} per the set point value using conventional PID and PI-Fuzzy control system.

As result, it is possible to say that the system could correct the change of the input voltage then the output voltage re-pursuit the set point.

Also, comparing the response of the fuzzy controller with the classical PID, the fuzzy has better response to correct this disturbance.

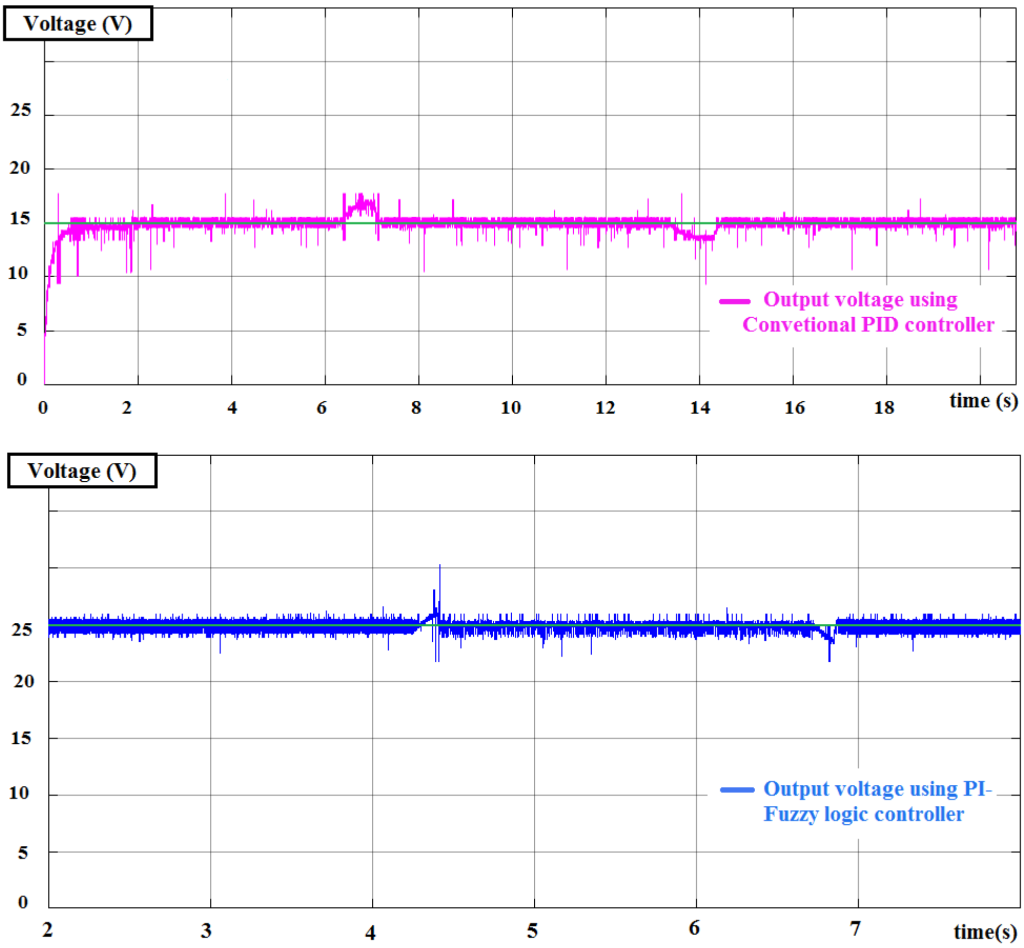

Figure 16. Reference pursuit using PID (Pink signal) and PI-Fuzzy logic Controllers (blue signal)

4.2. Load change case:

On the other hand, for a system control voltage, the system must keep the output voltage constant even with a change in load.

In this simulation, and to verify the good effectiveness of the proposed system, the load drops to another value over time.

For this example, the load bascule between 200 Ω and 80 Ω. And as shown in figure 17, for both control system when the load changes the system correct the created error, by adjusting the duty cycle of the PWM signal then the output voltage re-pursuit the chosen reference voltage.

Fuzzy logic control technique, in this case, shows better response in terms of speed to correct the error after load change.

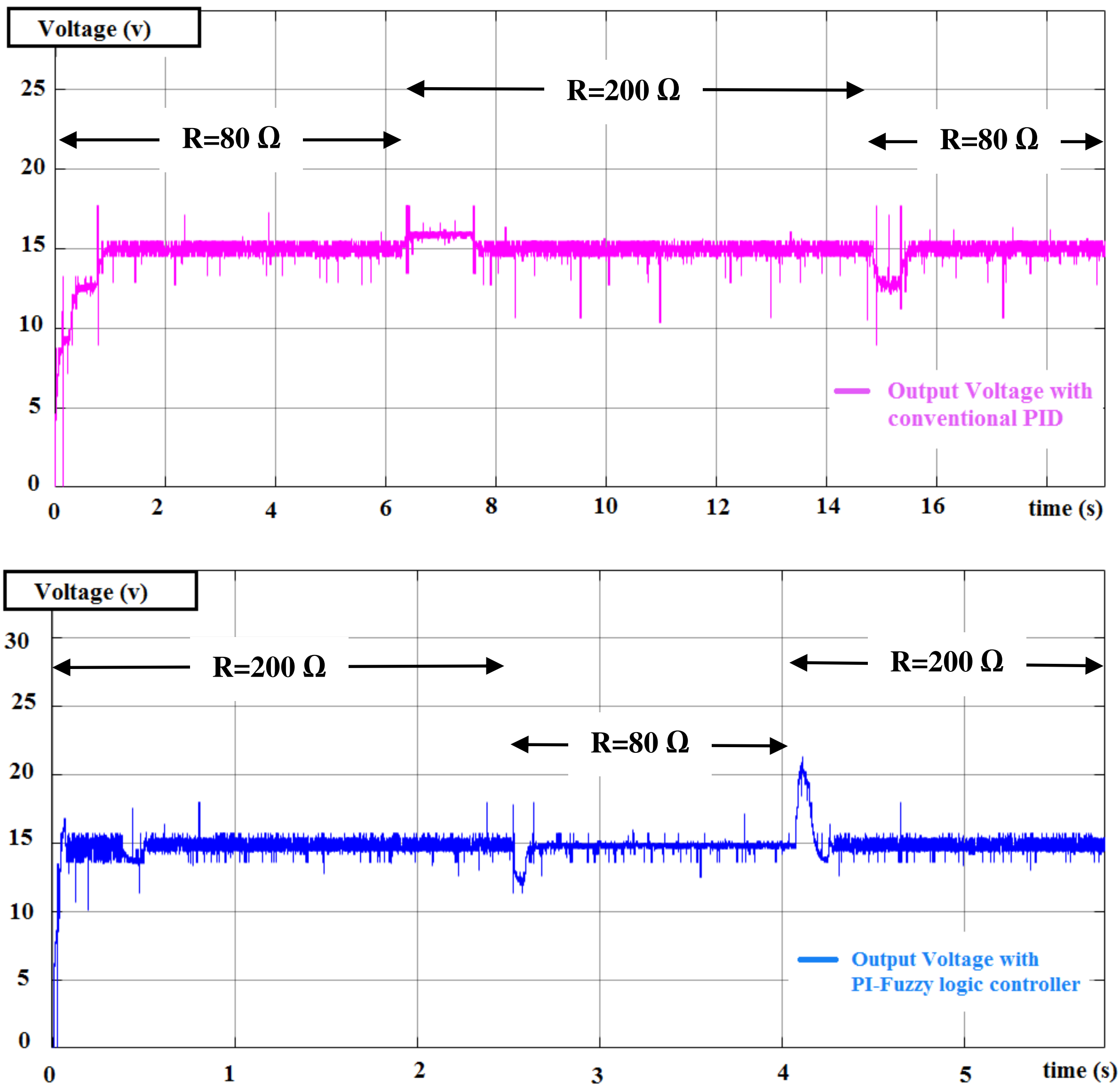

Figure 17. Reference pursuit in load change case

5. Conclusion

This paper treated a voltage control system for photovoltaic sources, which could be extended to other no-regular sources, using a DC-DC converter type SPEIC as an intermediate block between source and loads in order to guarantee the transfer of the power necessary to supply the latter.

SEPIC converters and as already mentioned are buck-boost converters with a very high performance and which can reach high voltage level easily.

For the control part, two control strategies are proposed namely the conventional PID controller and the PI-Fuzzy logic controller to control the transferred power to loads.

To validate the proposed system, servals simulations were treated under Matlab Simulink environment and implemented low-cost control board to improve the good behavior of this system in real-time simulations.

Due to the high performances of the control board: the Raspberry Pi 3, the work could also be extended to others control system techniques and algorithmes.

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