A New Low Cost Solar Array Emulator Based on Fuzzy and 32-Bit Microcontroller

Doaa Subhi[1], Rasha Thabit[2]

[1,2]Computer Techniques Engineering Department, Al-Rasheed University College, P.O.B. 6068, Al Jamaa, Baghdad, Iraq
([1]doaasubhi992@gmail.com, [2]rashathabit@yahoo.com)

Abstract- Solar photovoltaic (PV) energy attracted the attention of the electrical engineers and researchers because of its advantages in comparison with the traditional energy resources. The characteristics of the PV system are affected by the weather's changing condition therefore solar array simulators and emulators have been introduced as alternatives to the actual solar cell or array of cells. This paper presents a new solar array emulator based on Fuzzy and 32-bit microcontroller. The proposed emulator obtained current-voltage (I-V) characteristics curve that is almost identical with characteristics curve of the actual solar array. The proposed emulator proved its efficiency in terms of flexibility, reliability, cost, and complexity in comparison with the state-of-the-art emulators. The proposed emulator can be used in electrical engineering labs as a good alternative to the actual solar array cells.

Keywords- PV Emulators, Renwable Energy, Fuzzy Logic Control

I. INTRODUCTION

The continuous increment in population imply that there is a continuous need for energy resources [1]. Recently, the interest has been directed towards the renewable energy resources as a good alternative for the traditional energy resources where the latter are rapidly exhausted and they will be vanished in the near future. In addition, the process of burning the fossil fuels results in adverse effects on the humans and atmosphere [2].

Solar photovoltaic (PV) energy is one of the renewable energy resources that attracted the attention of the researchers because of its advantages such as quietness, cleanness, non-radiation, and its boundless amount. The PV characteristics are affected by the lighting and temperature, therefore, the maximum power point tracking (MPPT) technology has been utilized in PV applications [3], [4]. In some situations, the PV system engineers cannot realize the ideal PV characteristics to define the prospect and dynamic response of the MPPT because of the weather's changing conditions, therefore, different methods have been used to simulate the PV cells. The simulator consists of a power electronics circuit that can be used to generate the static and dynamic output characteristics of an actual solar cell or arrays of cells at different environmental and load conditions. PV source simulators are efficacious in terms of cost, compactness, and flexibility properties [5]. The initial phase of the presented simulators includes metal-halide lamps and temperature controlling devices which have been utilized to produce the illumination and temperature of PV arrays [6], [7], however, they suffer from the high cost and power consumption problems. Thereafter, many solar array simulators (SASs) have been presented to obtain the PV characteristics exactly. In [8]-[11], pulse width modulation (PWM) dc-dc converters have been used in high-power SAS systems in order to obtain the PV characteristics efficiently but they suffer from the problems of power waste, switching losses, and low conversion efficiency. Subsequently several improved SAS have been presented. For instance, in [2], an improved SAS has been presented which is based on using LLC resonant dc-dc converter. In this system, frequency modulation (FM) has been applied instead of the PWM. The converter of this system has a transformer which is used to isolate the electricity for safety demands and its output impedance has been regulated without shunt or serial resistors, therefore, it obtained high conversion efficiency. However, the system has some limitations such as the accretion of the printed area and the cost because of using the transformer, the use of diodes to control the current direction which increased the dissipated power, and the use of FM instead of PWM reduced the fitness and the reliability.

In [12], another SAS has been introduced which makes use of the benefits of analog and digital simulators. The simulator consists of a cascade of a 3-phase ac-dc rectifier and 3-phase dc-dc converter. A proportional-integral-derivative (PID) controller has been used to improve the dynamic response of the current loop. The simulator obtained the PV static and dynamic characteristics properly under various load and weather conditions. However, the main limitations of this system are the bulky size and high cost which make it not practical for educational laboratory.

In [13], a PV simulator using off-the-shelf DC power supply and buck convertor has been presented. In this system, a fan has been added to cool the dc power supply. The prototype used in this simulator reduces the time that is required to design and built the system. However, the main drawback of this system is the limited load ranges which makes it not workable under different load conditions, in addition, the use of the fan increased the power consumption.

Another PWM controlled PV simulator has been introduced in [14] which consists of Push-Pull dc-dc convertor with digital controller and isolating circuit. Artificial intelligent fuzzy control algorithm has been applied in this design to increase its accuracy. This simulator can comply with load characteristics and the I-V curve of the solar cell under different loads and conditions. The limitation of this simulator is the use of many switches and components which increased the power consumption.

In [15], another simple, low cost and high efficiency PV emulator has been developed which realizes the I-V characteristic under different loads and conditions based on buck dc-dc convertor and proportional-integral (PI) compensator. The limitation of this simulator is the reduction of accuracy because of the control method that is based on try and error.

To avoid the abovementioned limitations, this paper presents a new PV emulator which is based on using Fuzzy controlled synchronous buck dc-dc converter with STM-32 microcontroller. The proposed emulator characterized by the simplicity and the low cost because of using STM-32 microcontroller chip and soft buck convertor that consist of only two MOSFET transistors controlled by PWM signal and LC filter. In addition, the use of the Fuzzy control improved the flexibility and reliability of the emulator in comparison with the classical control methods such as P, PI and PID methods.

The rest of the paper is organized as follows: section 2 illustrates the proposed PV emulator, section 3 explains the experiments and their discussion, and section 4 contains the conclusions of this work.

II. THE PROPOSED PV EMULATOR

The proposed PV emulator in this paper mainly consists of the power stage, digital control module, and digital reference-generation circuit. A general block diagram of the proposed system is shown in Figure 1.
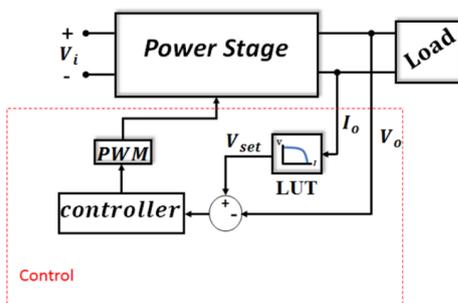

Figure 1. General block diagram of the proposed PV emulator

The power stage circuit is a single phase synchronous dc-dc buck convertor and its equivalent circuit is illustrated in Figure 2, in which Ro is a variable load resistance, io is the output

current and Vo is the output voltage. T1 and T2 are transistors which represent switches that are controlled by on-off duty cycle of PWM signal. The input voltage is directly delivered from the dc power supply. The L and C are the inductor and capacitor respectively, which provided the LC filter that is used to reduce the ripple of the output dc voltage. The L and C values must be chosen to stay on the continuous conduction mode (CCM) over all periods. Therefore, the LC filter of the proposed PV emulator has been designed based on the following equations [16]:

$$L \geq \frac{V_o \ (1 - D_{min})}{\Delta I_L \ f_S} \tag{1}$$

$$C \geq \frac{\Delta I_L}{\Delta V_O} \ \frac{1}{8 \ f_S} \tag{2}$$

Where D_{min} is the minimum duty cycle ratio, ΔI_L is the inductor current ripple, f_S is the switching frequency and ΔV_O is the allowable output voltage ripple. The buck convertor parameters are illustrated in Table I.
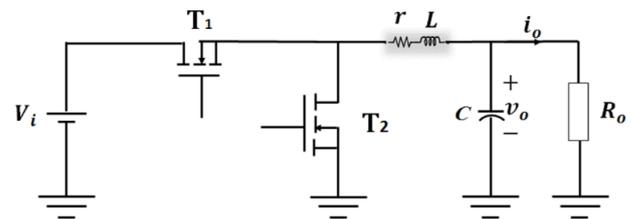

Figure 2. Buck convertor of the proposed PV emulator

TABLE I.   BUCK CONVERTOR PARAMETERS

Parameter	Value
Input voltage (V_i)	$25 \mp 10\%$ V
Output voltage (V_o)	$0 - 23$ V
ΔV_o	$\leq 5\%$
Output current (I_o)	$0.25 - 4$ A
Switching frequency (f_s)	50 kHz
Inductor + its internal resistance ($L + r$)	1 mH + 0.013 Ω
Output capacitor (C)	50 μF

The control part of the proposed PV emulator mainly consists of the microcontroller IC and the software programming. The STM 32-bit microcontroller IC has been used and programmed using fuzzy logic control algorithm (FLC). A general block diagram of the proposed fuzzy based control method is shown in Figure 3 which has four major stages that are fuzzification, defuzzification, knowledge base, and decision maker.

The fuzzification stage is used to convert the input data into its corresponding semantic values whereas the defuzzification is doing the opposite. The knowledge base stage contains if-then rules and the database which determines the relation between fuzzy sets and fuzzy rules. The decision maker stage executes the operations according to the rules.
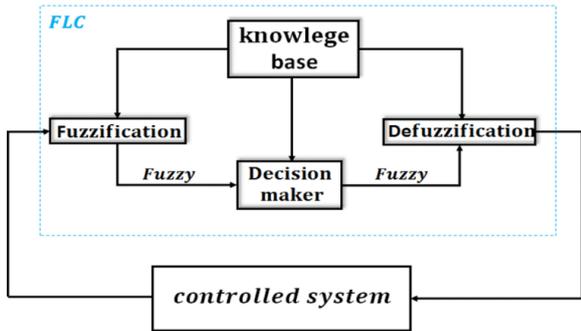
Figure 3.   General block diagram of the proposed FLC method

$e(n)$ /$\Delta\,e(n)$	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NL	NL	NL
NM	NL	NL	NM	NM	NL	NL	NL
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NL	NS	Z	PS	PM	PL
PS	NL	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PL	PL	PL	PL	PL	PL

FLC can be designed easily using the fuzzy set "if, then" with the defined rules by the user. The input signals of FLC are the error signal $e(n)$ and the change in the error signal $\Delta\,e(n)$ which can be calculated using eq. (3) and eq. (4), respectively. The error signal $e(n)$ is the difference between a set voltage V_{set} and the converter output voltage V_o.

$$e(n) = V_{set} - V_o \qquad (3)$$

$$\Delta\,e(n) = e(n) - e(n-1) \qquad (4)$$

The set signal is calculated using eq. (5), where $\Delta e(n)$ is the output of FLC set voltage signal and e(n-1) is the previous set signal.

$$e(n) = e(n-1) - \Delta\,e(n) \qquad (5)$$

Table II represents the FLC rules that are used to control the operation of the proposed PV emulator according to the comparison results of the error and the difference in error signals. The rules can be summarized as follows:

- *Positive large (PL) and negative large (NL): these cases mean the output voltage signal value is far from its set value.*

- *Negative medium (NM) and positive medium (PM): these cases mean the output voltage signal is near the set value.*

- *Negative small (NS) and positive small (PS): these cases mean that the output voltage is very close to the set value.*

- *Zero (Z): this case means the output voltage signal equal to the set voltage signal.*

Depending on the fed back value from FLC the pulse width modulation (PWM) switching signal will be generated to control the on-off duty cycle of T1 and T2.

Figure 4 shows the Simulink model of the proposed solar array emulator in which the output signals Vo and Io sensed by voltage sensor and current sensor, respectively. Io is used to generate the set voltage by using information that are stored in the look up table (LUT). Then the set voltage is compared with the output voltage Vo to generate the error signal. The error signal passed through the FLC to produce the proper signal to PWM generator which controls the switching of the two transistors T1 and T2.
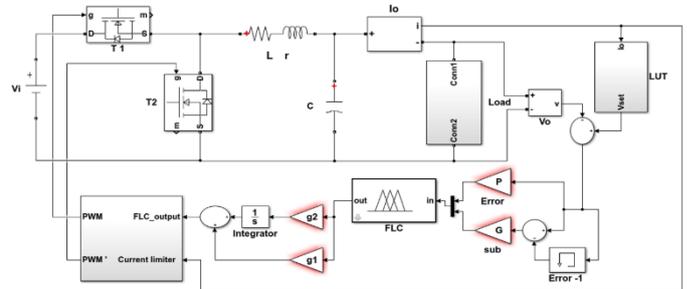

Figure 4.   Simulink module of the proposed solar array emulator

The circuit of the proposed PV emulator has been built on the double side Printed Circuit Board (PCB) as shown in Figure 5. In the implemented hardware, we added input capacitor to stabilize the input voltage and to reduce its ripple. The two output capacitors with 100μF are connected together to give an output capacitor of 50μF.
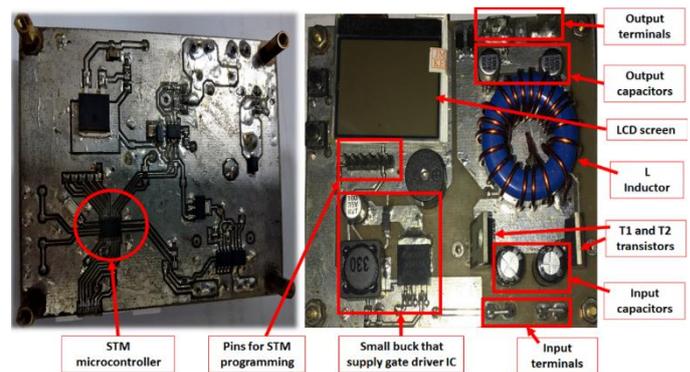

Figure 5.   The proposed solar array emulator prototype.

Solar cells could be represented as shown in Figure 6 where Rsh and Rs are the intrinsic shunt and serial resistors of the cell, respectively. A current source Iph represents the cell photocurrent which is a function of irradiance and solar array temperature (T). In order to build a successful PV emulator, it must flow the I-V curve of actual solar cell under different conditions. First, the emulator must be provided by three basic points (open circuit, short circuit, and MPP of current and voltage) of solar cell that needed to emulate it, then the emulator will evaluate the other points of I-V curve.
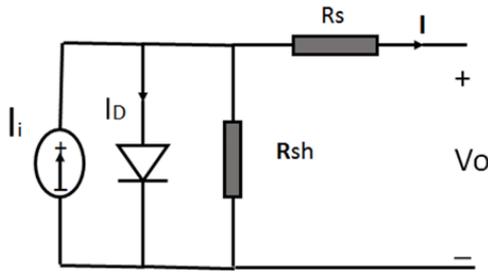
Figure 6.   Solar array modeling

Figure 7.   Manufacturer I-V curve for the actual solar array at different irradiance levels.

50w Lorenz LC50-12M solar panel selected as an actual solar array and a LUT information saved from its characteristics at different conditions. The solar array manufacturer I-V curve with different irradiance levels is shown in Figure 7. The figure illustrates that for the irradiance level 1000 W/m2, the open circuit voltage is 22V with a short circuit current equal to 3.25A, and the voltage and current at the maximum power point are equal to 18V and 2.78A, respectively. The implemented prototype of the proposed emulator obtained the above mentioned characteristics of the solar cell as shown in the following section.

III.   THE EXPERIMENTAL RESULTS AND DISCUSSION

The performance of the proposed PV emulator has been evaluated practically under different loads and irradiance levels. To prove the efficiency of the proposed control method, two control setups have been applied where the first setup is based on PI compensator while the second setup is based on the proposed FLC method. The simulation experiments are explained in the following subsection, followed by the hardware experimental results and the final section contains the comparisons of the proposed emulator with the state-of-the-art emulators.
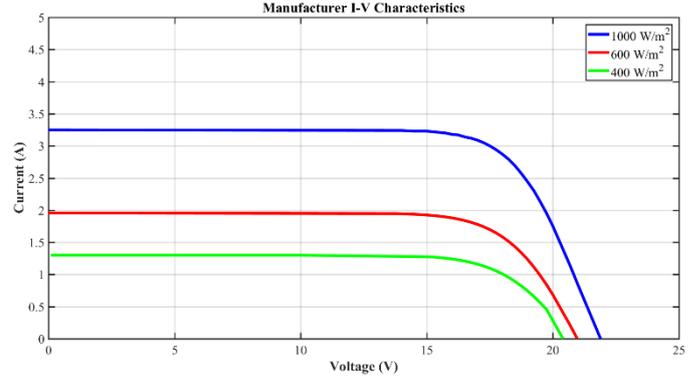
A.   Simulation Experiments and Results

An output voltage signal to calculate the error signal. Thereafter, the error signal is passed to the controller to enhance its output and the output of the controller is compared with a sawtooth function to get a PWM signal. The performance of the proposed solar array simulator based on FLC method has been tested and compared with the performance of the PI based model to prove its efficiency. Figure 8 and Table III present the comparison results for the output voltage of the emulator at open circuit case (i.e., no load is connected to the output terminals). The results proved that the oscillation and overshooting in the signal using FLC model are less than that of the PI model.

TABLE III.   OUTPUT VOLTAGE COMPARISON AT OPEN CIRCUIT

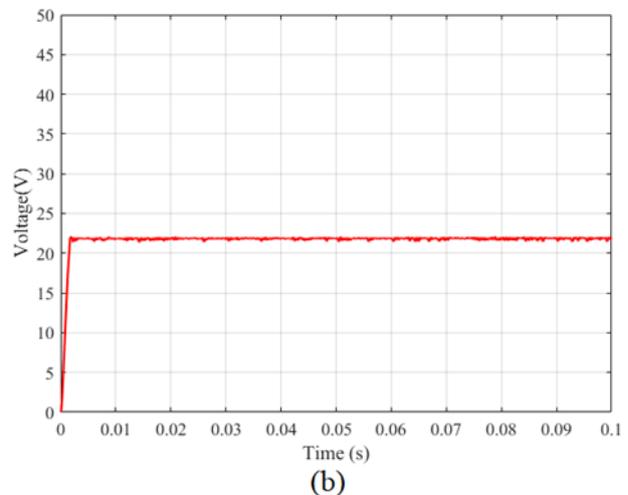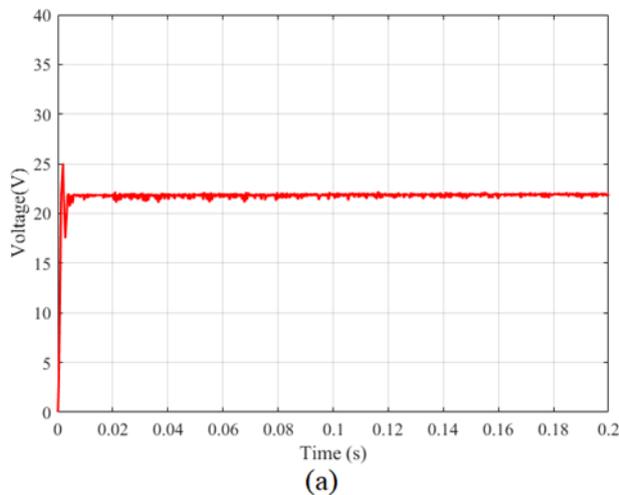|	Ripple	Overshooting
PI model	$\cong$ 5%	$\cong$ 15%
FLC model	$\cong$ 3%	No overshooting

Figure 8.   Output voltage of the emulator at open circuit point: (a) PI model, and (b) FLC model

Figure 9 demonstrates the minimum current value when a resistive load of 88 Ω is connected to the simulator using PI

compensator and FLC. The results proved that both models are still working in the continuous conduction mode (CCM).
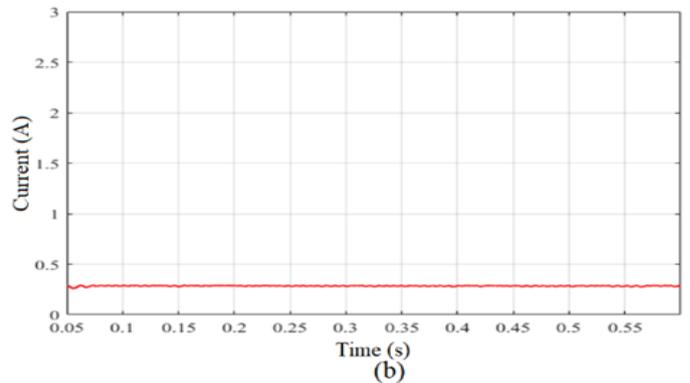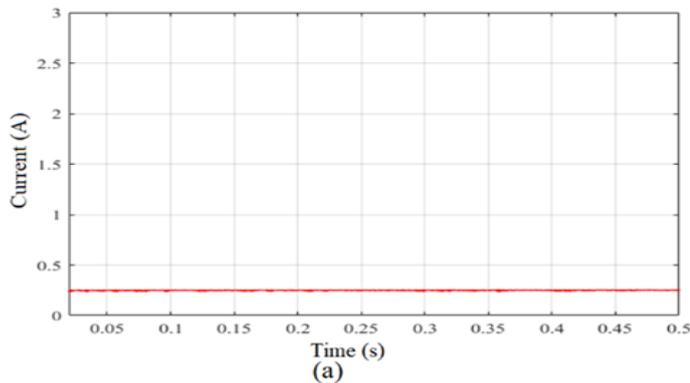

Figure 9. Minimum load current at resistive load 88 Ω: (a) PI compensator model, and (b) FLC model.

To draw the PV characteristic for PI compensator and FLC models, the currents and voltages have been tested at different loads for irradiance levels 600 W/m2 and 1000 W/m2. The results are illustrated in Figure 10 and Table IV which proved that PV curve for PI compensator has more fluctuation than that for the proposed FLC model.

TABLE IV.   COMPARISON IN SWING VALUES OF PV CHARACTERISTIC FOR PI AND FLC MODELS

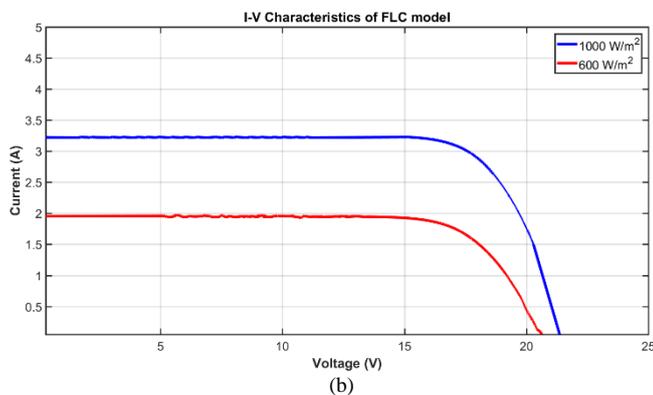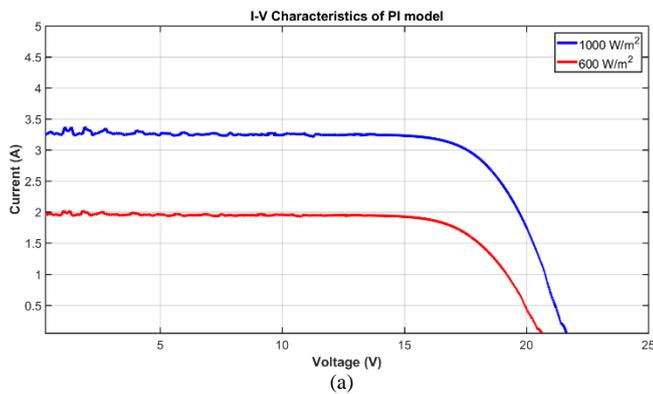| Irradiance W/m^2		PI compensator	FLC model
600	(0-5) volt	0.1 A	0
	(5-10)volt	0.05 A	0.03 A
1000	(0-5) volt	0.2 A	No swing
	(5-10)volt	0.1 A	No swing

B. Hardware Experiments and Results

According to the simulation experiments, the proposed emulator using FLC based on PID obtained better results than PI model therefore the hardware prototype has been implemented for the FLC algorithm only (as explained in section 2). The implemented emulator has been tested at different loads and irradiance levels 600 W/m2 and 1000 W/m2 in order to compare its PV characteristics with the manufacturer PV characteristics that have been mentioned in section 2. The comparison results are shown in Figure 11 and they proved that the emulated characteristics are close to the actual characteristics with very small error that can be considered satisfactory.

Figure 10. PV characteristics of solar array simulator at different irradiance levels for: (a) PI compensator model, and (b) FLC model.
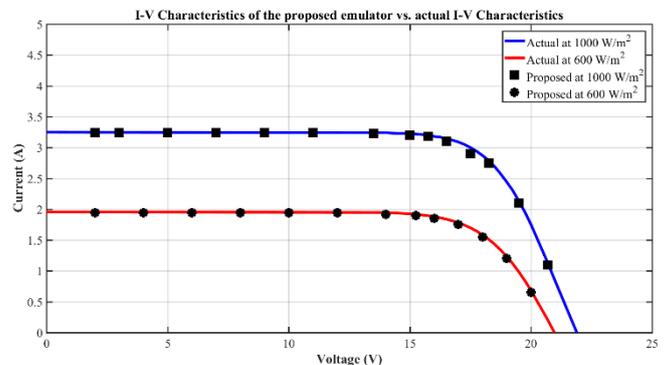

Figure 11. PV curve for the proposed emulator vs. manufacturer PV curve

The maximum power point for the proposed emulator has been found when the load is 6.5 Ω, the output voltage and current are equal to 18V, 2.8A respectively as shown in Figure 12. The voltage ripple, current ripple, and the maximum overshooting are still in the design criteria for different loads.
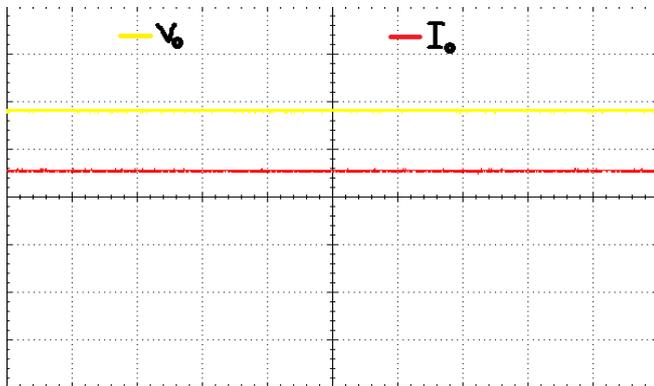

Figure 12. Voltage and current waveforms of the proposed emulator at MPP (5A/div, 10V/div, 2ms/div).

C. Comparison with the state-of-the-art

To prove the efficiency of the proposed emulator, this section presents a general comparison of the proposed emulator with the state-of-the-art emulators from [2], [12]-[15]. Table V summarizes the comparison of the proposed emulator with the state-of-the-art emulators. The advantages of the proposed emulator can be explained as follows:

• Better flexibility and reliability: The use of FLC based on PID improved the reliability and flexibility of the proposed emulator in comparison with the PI and PID based control algorithms that have been used in [2], [12], [13], and [15]. In addition, the reliability of the proposed emulator is better than that in [2] because of using PWM instead of FM. The improved reliability and flexibility contribute in obtaining more accurate PV characteristics.

• Reduced size and cost: The use of STM-32 bit microcontroller contributes in reducing the size and cost of the implemented hardware in comparison with the emulators in [12]-[15] that used DSP TM320F28335 32-bit [12] [13], PC multifunction acquistic card [14], and ARM cortex M4 32- bit [15]. In addition, the proposed emulator is better than the emulator in [2] in terms of size and cost since the later used a transformer and diodes.

• Reduced complexity: The use of buck converter that consists of two transistors and LC filter contributes in reducing the complexity of the implemented hardware in comparison with the emulators in [2], [12]-[14].

• Reduced power consumption in the circuit: The simple design of the proposed emulator reduced the consumption of the power inside the circuit in comparison with the emulators in [2], [13], and [14]. The use of the transformer and diodes in [2], the fan in [13], and many switches in [14] increased the amount of power dissipated in their circuits.

TABLE V. COMPARISON OF THE PROPOSED EMULATOR WITH THE STAT-OF-THE-ART EMULATORS

Emulator	Control algorithm	Microcontroller type	The merit of the proposed emulator
C. Chang et al. [2]	P & O	Not implemented	The proposed emulators in better than the emulator in [2] in terms of: 1- Flexibility and reliability. 2- Size and cost. 3- Complexity. 4- Power consumption.
A. Koran et al. [12]	PI and PID	DSP TM320F28335 32-bit	The proposed emulators in better than the emulator in [12] in terms of: 1- Flexibility and reliability. 2- Size and cost. 3- Complexity.
S. Gadelovits et al.[13]	PI	DSP TM320F28335 32-bit	The proposed emulators in better than the emulator in [13] in terms of: 1- Flexibility and reliability. 2- Size and cost. 3- Power consumption.
J. Zhang et al [14]	Fuzzy based on PI	PC multifunction acquistic card	The proposed emulators in better than the emulator in [14] in terms of: 1- Size and cost. 2- Complexity. 3- Power consumption.
J. Gonzalez-Llorente et al [15]	PI	ARM cortex M4 32- bit	The proposed emulators in better than the emulator in [15] in terms of: 1- Flexibility and reliability. 2- Size and cost.
The proposed emulator	Fuzzy based on PID	STM-32 bit	The proposed emulator can be considered as a better candidate to be used in electrical engineering labs.

IV. CONCLUSIONS

In this paper, a new solar array emulator has been proposed as a good alternative to the actual solar array in order to be used in electrical engineering labs. The proposed emulator is based on FLC and STM-32 bit microcontroller. The implemented prototype obtained excellent solar array characteristics that are almost identical to the actual PV characteristics under different loads and irradiance levels. The experimental simulation results proved the efficiency of FLC in comparison PI compensator. The comparisons with the state-of-the-art emulators proved the efficiency of the proposed emulator in terms of flexibility, reliability, size, cost, complexity, and the power consumption. As a conclusion, the proposed emulator can be considered as a better candidate to be used in electrical engineering labs.

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Doaa Subhi received her B.S.c degree in Electrical Engineering from University of Bagdad, Iraq, in 2013 and M.S.c degree in Electrical Engineering from University of Baghdad, Iraq, in 2016. Her research interest is in the area of control system and renwable energy.