Emulation of Different Photovoltaic Materials and Technologies using PV Array Emulator with Linear Quadratic Regulator

Mustapha ALAOUI, Hattab MAKER, Azeddine MOUHSEN, Hicham HIHI

Abstract— This paper proposes the emulation of different photovoltaic (PV) materials and technologies using an innovative PV array emulator based on Linear Quadratic Regulator (LQR), this electronic power device aims to reproduce faithfully the real PV module behavior independently on environmental conditions change, it allows scientists, industrials and researchers to carry out their measurements and experiences on PV systems without depending on PV panels, which require the sun to perform tests and do not allow repetitive measurements at the desired temperature (T) and irradiance (G). Moreover, PV modules actually are very expensive and require a large area to reach some powers, all these limitations and others are handled using this designed PV emulator. Simulation results using Matlab Simulink software are given and analyzed in order to evaluate the performances of the developed equipment and to judge its efficiency and capacity to track rapidly and accurately the I-V characteristic of different PV modules.

Index Terms— PV array emulator, Linear Quadratic Regulator, PV technologies, I-V characteristic, power converter, optimization.

1 INTRODUCTION

With a large interest in renewable energy nowadays in order to combat climate change and contribute to the sustainable development, many researchers and manufacturers are interested in the study of photovoltaic (PV) systems and all related subjects which concern PV modeling and control, power optimization, solar connected inverters and many other fields. Those studies require photovoltaic array emulators which can reproduce the electrical behavior of the desired PV panel at any time without depending on the weather conditions [1] , this will allow researchers to carry out efficiently their experiences and tests on photovoltaic energy without needing real PV panels which are generally expensive and require a large space [2]–[7]. This work consists of the development of a new solar emulator based on the Linear Quadratic Regulator (LQR) in order to track faithfully the I-V characteristic of the PV module and optimize the functioning of the full system. The proposed PV emulator is based on a DC-DC buck converter with closed-loop voltage control. The reason behind using LQR is its ability to deal with the non-linearity of both the power topology and the I-V characteristic [8], and its robustness against external disturbances, dynamic load change and variation of atmospheric parameters, unlike many existing PV emulators which suffer from inaccuracy in some zones of PV module I-V curve, besides their poor dynamic response [9]. Moreover, this controller ensures good performances in terms of speed, accuracy and overshoots limitation so that the designed circuit can meet the requirements and have a similar output response as a real PV module. Different PV material technologies are used so as to judge the ability of the proposed system to emulate accurately various types of PV module characteristics of power, material and manufacturers [6].

2 Emulation System Components

Figure 1 illustrates the block diagram of the proposed system, it consists essentially of the power part which contains the DC-DC buck converter, and the control part which consists of the reference generator used to deliver the constant voltage reference, besides the controller to ensure the required performances of the PV emulator.
The Matlab Simulink Model including the PV emulator with The PV model based on one diode two resistances model (1D-2R) [4], [6] is shown in figure 2.

- *Mustapha ALAOUI is currently pursuing Ph.D. degree program in power electronic and renewable energy in Hassan First University, Morocco. E-mail: mu.alaoui@uhp.ac.ma*
- *Hattab MAKER is currently Professor at Hassan First University, Morocco, his main research activity concerns renewable energy, power management and power electronic, E-mail: hattabmaker@gmail.com*
- *Azeddine MOUHSEN is currently Professor at Hassan First University, Morocco, his main research activity concerns Energy transfer, Instrumentation and measurements, sustainable energy, radiation-matter, applied optics, E-mail: az.mouhsen@gmail.com*
- *Hicham HIHI is currently Professor at Cadi Ayyad University, Morocco, his main research activity concerns Renewable Energy, Bond Graph Approach, Nonlinear and Hybrid Systems Control, Automation.E-mail: h.hihi@uca.ac.ma*

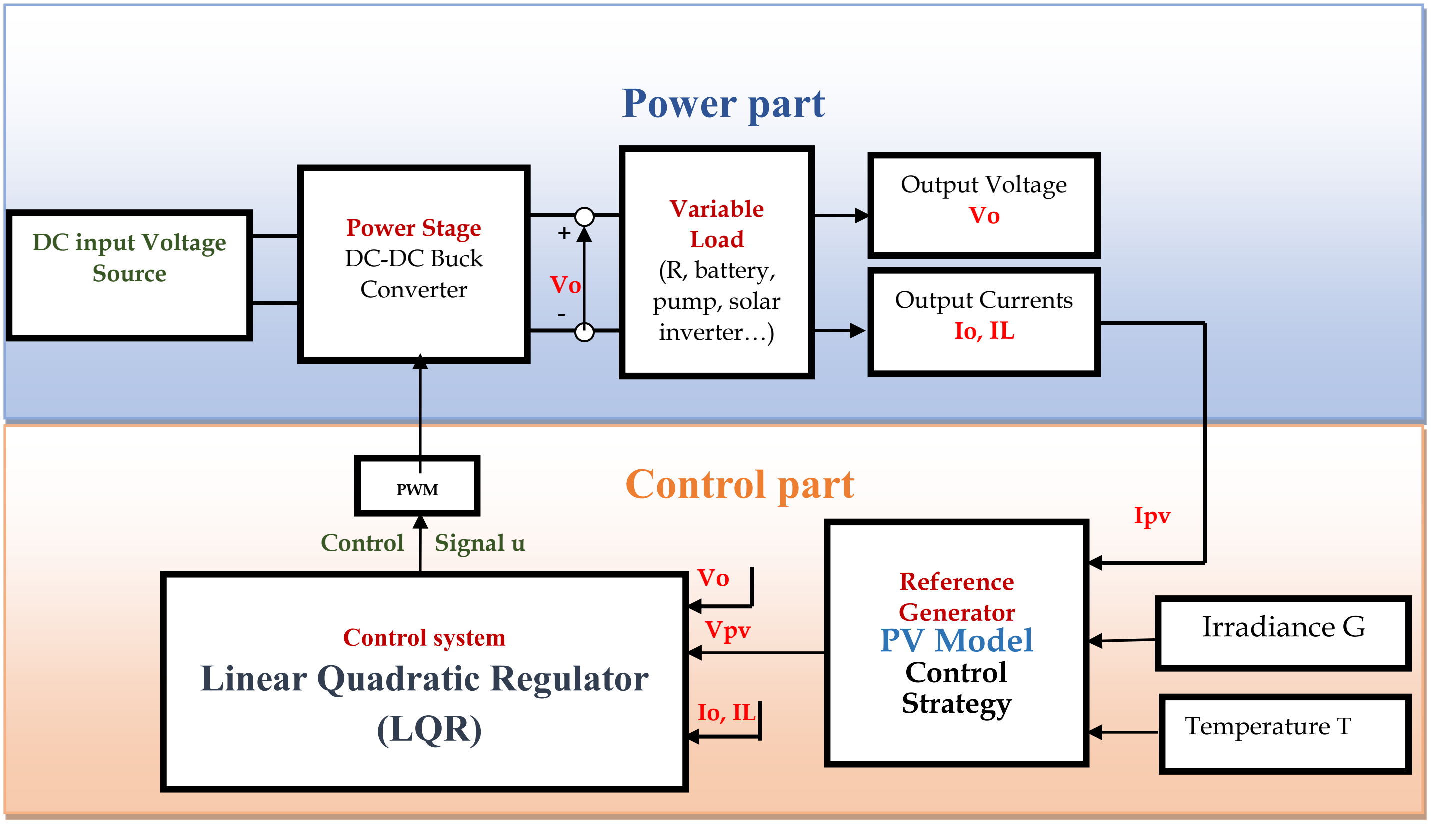

Fig. 2. PV array emulator components

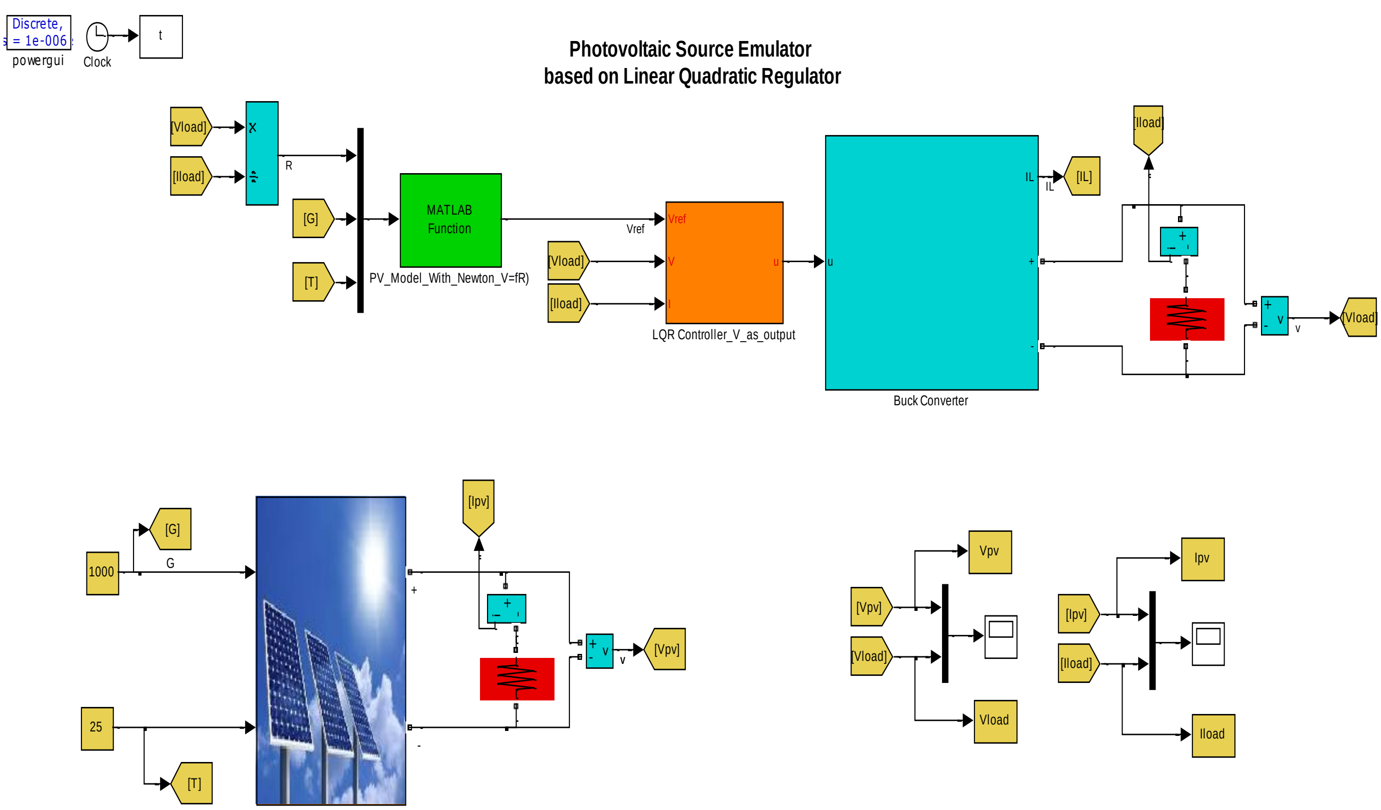

Fig. 1. Matalb Simulnik Model of the proposed PV emulator

3 LQR Design

The Linear Quadratic Regulator (LQR) has been chosen to control the DC-DC buck converter in order to provide the system with an optimal control taking into consideration the load variation and the environmental conditions change, it can ensure a good compromise between accuracy, speed and energy consumption optimization in the control law [11].

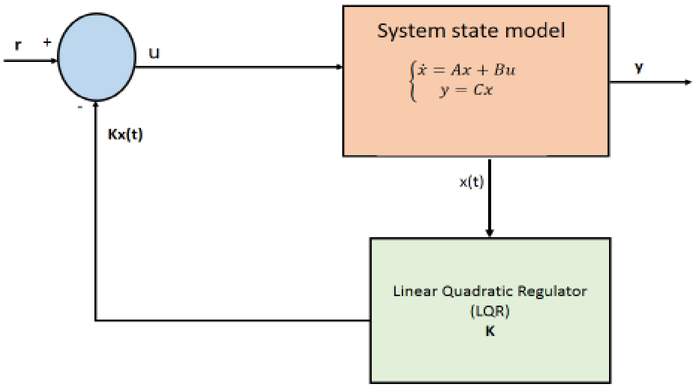

Fig. 3. Synoptic schema of the system with LQ controller

The cost function J to be minimized is the following:

$$J(u) = \int_0^{+\infty} (x^T(t)Qx(t) + u^T(t)Ru(t))dt \quad (1)$$

Where:

- Q and R are positive definite matrix.
- u(t) is the control input
- x(t) is the state vector :

$$x(t) = \begin{pmatrix} Vref - Vo \\ Io \\ \int Vref - Vo \end{pmatrix} \quad (2)$$

With Vref is the reference voltage, Vo is the output voltage and Io is the output current. We are penalizing both the state and the control effort, and the objective is to find the control input u which minimizes the cost function J. The power converter parameters are listed below:

TABLE 1

DC-DC BUCK CONVERTER PARAMETERS

Parameter	Value
Input voltage Vdc	70 V
Capacitance C	3 µF
Inductor L	2 mH
Switching frequency f	100 KHz

The state model matrix of the DC-DC buck converter are expressed as:

$$A = \begin{pmatrix} \frac{-1}{RC} & \frac{1}{C} & 0 \\ -1/L & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad (3)$$

$$B = \begin{pmatrix} 0 \\ \frac{Vdc}{L} \end{pmatrix} \quad (4)$$

$$C \quad (5)$$

The matrix Q and R are chosen as below

$$Q = \begin{pmatrix} \frac{30}{L * C} & 0 & 0 \\ 0 & \frac{400}{L} & 0 \end{pmatrix} \quad (6)$$

$$R = 1 \quad (7)$$

The LQR gains have been computed using LQR command of Matlab.

4 STEADY STATE STUDY

In this section, a comparison is done between the output I-V curve of the proposed PV emulator with the expected I-V characteristic of the real PV module, by this comparison, we can evaluate the performances of the designed PV emulator in terms of accuracy, speed, and overshoot limitation.

4.1 Emulation of Monocrystalline PV module

The following table illustrates the electrical characteristic of the studied PV module.

TABLE 2

ALLMAX PLUS MONOCRYSTALLINE PV MODULE CHARACTERISTICS UNDER STC CONDITIONS

Parameter	Value
Peak rated power Pmpp	335 W
Open circuit voltage Voc	46.1 V
Short circuit current Isc	9.4 1A
Maximum power point voltage Vmpp	37.8V
Maximum power point current Impp	8.87A
Temperature coefficient of Isc : ki	0.053%/K
Temperature coefficient of Voc : kv	-0.31%/K
Temperature coefficient of power: kp	-0.41%/K

The I-V curve of the PV emulator with the PV module under STC conditions is presented in figure 4.

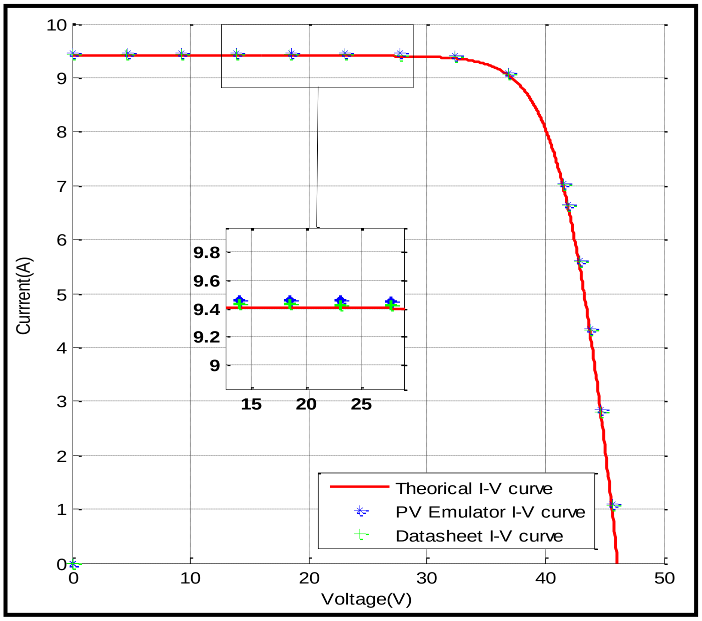

Fig. 4. Comparison between I-V curve characteristic of ALLMAX PLUS Monocrystalline PV model, real PV module and PV emulator under STC conditions

As shown in figure 4, the designed PV emulator can generate accurately the voltage and current outputs as a real monocrystalline PV module for any operating point in the I-V curve since the steady-state error is negligible, so it can efficiently imitate the electrical behavior of PV sources.

4.2 Emulation of Polycrystalline PV module

TABLE 3

POLYCRYSTALLINE HARVEST PV MODULE CHARACTERISTICS UNDER STC CONDITIONS

Parameter	Value
Peak rated power Pmpp	285 W
Open circuit voltage Voc	38.3V
Short circuit current Isc	9.64 A
Maximum power point voltage Vmpp	31.4 V
Maximum power point current Impp	9.06 A
Temperature coefficient of Isc : ki	0.05 %/K
Temperature coefficient of Voc : kv	-0.29%/K
Temperature coefficient of power: kp	-0.39%/K

Figure 5 emphasizes the previous results of monocrystalline PV modules since the performances are remaining the same even with the change of technology, power and manufacturers.

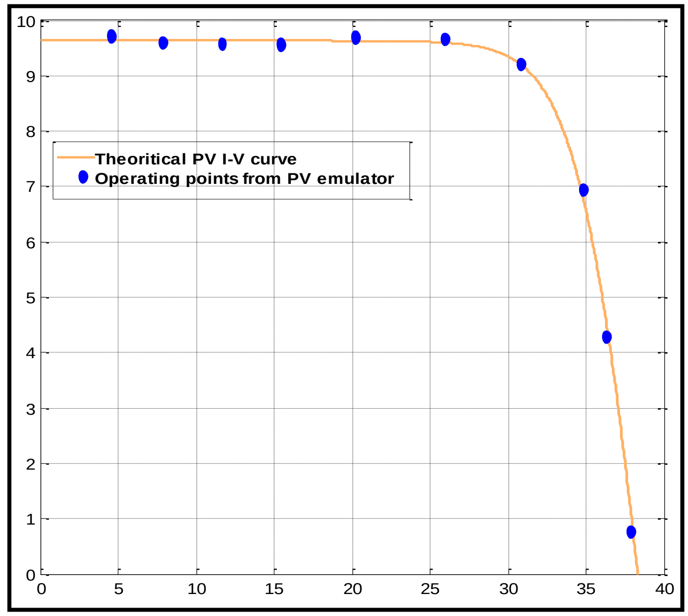

Fig. 5. Comparison between I-V curve characteristic of Harvest Polycrystalline PV model, real PV module and PV emulator under STC conditions.

4.3 Emulation of Amorphous PV module

TABLE 4

NEXPOWER AMORPHOUS PV MODULE CHARACTERISTIC UNDER STC CONDITIONS

Parameter	Value
Peak rated power Pmpp	160 W
Open circuit voltage Voc	85.5 V
Short circuit current Isc	2.57 A
Maximum power point voltage Vmpp	65.9 V
Maximum power point current Impp	2.43 A
Temperature coefficient of Isc : ki	0.07%/C°
Temperature coefficient of Voc : kv	-0.32 %/ C°
Temperature coefficient of power: kp	-0.28%/ C°

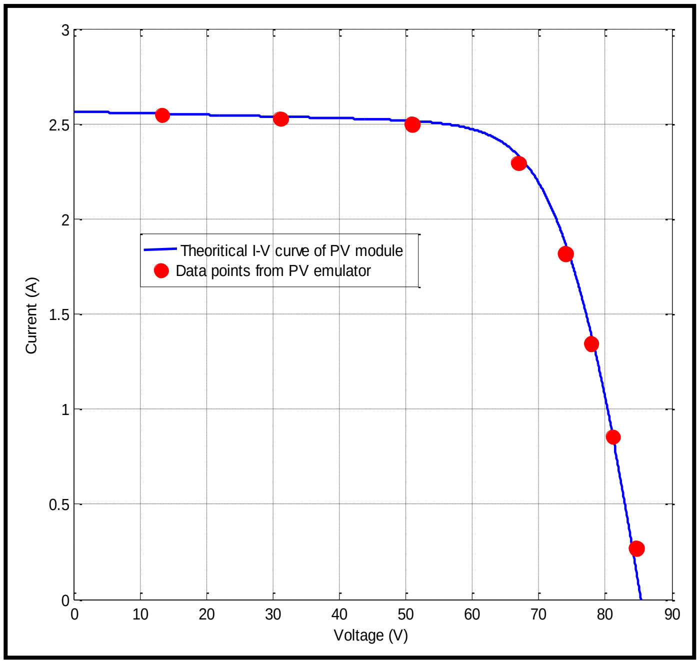

Fig. 6. *Comparison between I-V curve characteristic NexPower Amorphous PV model, real PV module and PV emulator under STC conditions.*

It is clearly shown according to figure 6 that the proposed PV emulator is able to deliver the same I-V curve as a PV module for amorphous PV technology. So we can conclude that the static performances of the PV emulator are maintained at the same level for different technologies, power and PV module characteristics.

5 Dynamic Study

In this part, the dynamic performances of the proposed PV emulator are evaluated in regards to the ability to track the PV module output current and voltage under weather parameters change of temperature and irradiance. Besides, the transient response is analyzed too so as to show the settling time of the PV emulator and the output ripples of the DC-DC buck converter. It is obvious from figure 7 that the proposed circuit has good dynamic performances, the settling time does not exceed 300 µs, and the current and voltages ripples are too small, furthermore, the developed system is endowed with a good level of accuracy thanks to its modern linear quadratic controller, which ensures an optimal trade-off between accuracy, speed and energy optimization.

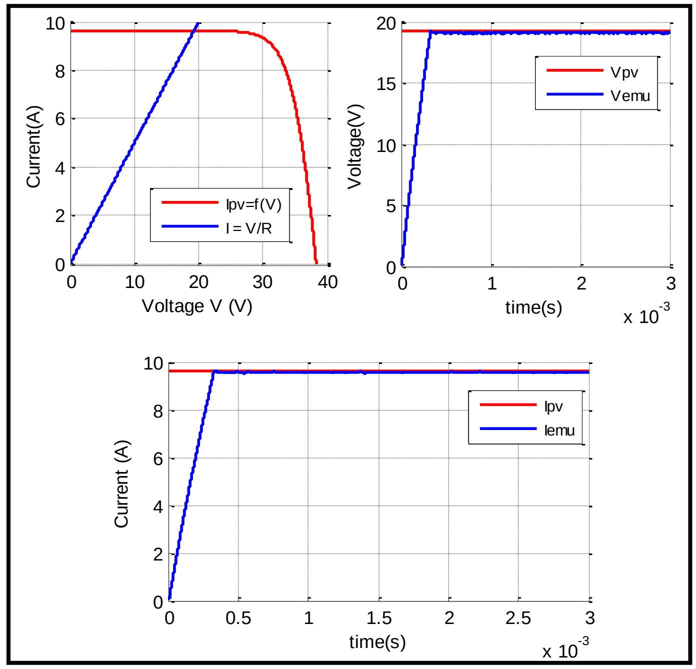

Fig. 7. *The output current and voltage with the I-V curve of the proposed PV emulator for R = 2 Ω under STC conditions*

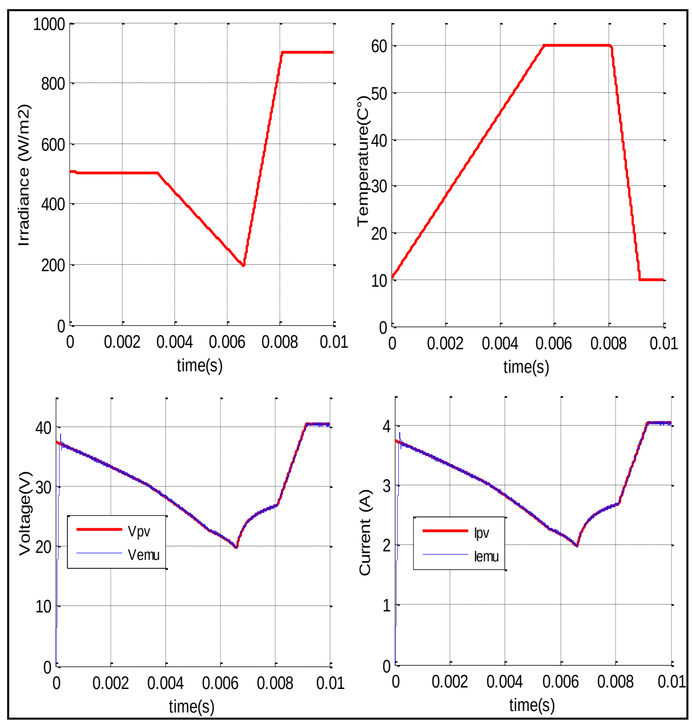

Fig. 8. *PV source Emulator under temperature and irradiance variation*

As depicted in figure 8, we have considered a random variation of temperature and irradiance in order to test the ability of the electrical circuit to deliver the same outputs as an actual PV module, and effectively, the proposed PV emulator tracks accurately and rapidly the PV module current and voltage under the variation of atmospheric conditions, so we can rely on this power electronic device to perform faithfully our experiences.

6 Conclusion

In this paper, an optimal and accurate PV source emulator has been presented, this novel equipment has as purpose to mimic the electrical behavior of real PV module regardless of atmospheric condition change, unlike actual PV modules which depend strongly to the weather parameters and do not allow carrying out measurements in desired conditions. The Linear Quadratic Regulator has been employed to meet the requirements of PV emulation in terms of accuracy, speed, overshoot limitation and dynamic I-V curve tracking. Moreover, Several types of PV module technologies and materials have been selected to be emulated, those PV modules have different characteristics and are selected from various manufacturers, the reason behind that is to validate the functioning of the proposed PV emulator with different cell technologies and materials so that the developed circuit can be able to maintain the same performances for any PV source. Further work will be dedicated to the experimental validation of the developed PV source emulator with MPPT algorithms and connected solar inverters.

REFERENCES

[1] R. Ayop and C. W. Tan, "A comprehensive review on photovoltaic emulator," Renewable and Sustainable Energy Reviews, vol. 80, pp. 430–452, Dec. 2017, doi: 10.1016/j.rser.2017.05.217.

[2] M. C. Di Piazza and G. Vitale, Photovoltaic sources: modeling and emulation. London: Springer, 2013.

[3] M. Alaoui, H. Maker, and A. Mouhsen, "An Accurate Photovoltaic Source Emulator with High-Bandwidth Using a Backstepping Controller," in 2019 4th World Conference on Complex Systems (WCCS), 2019, pp. 1–6, doi: 10.1109/ICoCS.2019.8930786.

[4] R. Ayop and C. W. Tan, "Rapid Prototyping of Photovoltaic Emulator Using Buck Converter Based on Fast Convergence Resistance Feedback Method," IEEE Transactions on Power Electronics, vol. 34, no. 9, pp. 8715–8723, Sep. 2019, doi: 10.1109/TPEL.2018.2886927.

[5] I. Moussa and A. Khedher, "Photovoltaic emulator based on PV simulator RT implementation using XSG tools for an FPGA control: Theory and experimentation," International Transactions on Electrical Energy Systems, vol. 29, no. 8, p. e12024, 2019, doi: 10.1002/2050-7038.12024.

[6] M. Shahabuddin, A. Riyaz, M. Asim, M. M. Shadab, A. Sarwar, and A. Anees, "Performance Based Analysis of Solar PV Emulators: A Review," in 2018 International Conference on Computational and Characterization Techniques in Engineering & Sciences (CCTES), Lucknow, India, 2018, pp. 94–99, doi: 10.1109/CCTES.2018.8674082.

[7] Z. Rasin, M. Fazlur Rahman, M. Azri, M. Hairul Nizam Talib, and A. Jidin, "Photovoltaic Emulator for Grid-connected Quasi-Z-Sorce Inverter," International Journal of Power Electronics and Drive Systems (IJPEDS), vol. 9, no. 4, p. 1976, Dec. 2018, doi: 10.11591/ijpeds.v9.i4.pp1976-1988.

[8] S. M. Azharuddin et al., "A Near Accurate Solar PV Emulator Using dSPACE Controller for Real-time Control," Energy Procedia, vol. 61, pp. 2640–2648, 2014, doi: 10.1016/j.egypro.2014.12.266.

[9] R. Ayop and C. W. Tan, "A comparison study of interpolation and circuit based photovoltaic mathematical models," in 2016 IEEE International Conference on Power and Energy (PECon), Melaka, Malaysia, 2016, pp. 626–631, doi: 10.1109/PECON.2016.7951636.

[10] J. P. Ram, H. Manghani, D. S. Pillai, T. S. Babu, M. Miyatake, and N. Rajasekar, "Analysis on solar PV emulators: A review," Renewable and Sustainable Energy Reviews, vol. 81, pp. 149–160, Jan. 2018, doi: 10.1016/j.rser.2017.07.039.

[11] G. Hovland, "Linear Quadratic Regulator Control (LQR)," p. 22, 2004.