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Design of a renewable based PV power supply system for a machine laboratory: Operation and performance analysis

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ABSTRACT

Solar energy stands out as a promising solution to global electricity challenges, holding substantial potential for meeting daily energy needs sustainably. This study addresses the critical issue of voltage fluctuations inherent in solar power supply, presenting a comprehensive design and implementation of a 25-kilowatt photovoltaic (PV) system for an electrical machine laboratory of the faculty. The integrated system, comprising a DC-DC converter, maximum power point tracking (MPPT) algorithm-based controller, three-phase inverter, and different load types, is strategically orchestrated to optimize performance and mitigate voltage inconsistencies. A neat simulation design in the MATLAB/Simulink environment ensures a thorough evaluation of system dynamics, demonstrating the system's capacity for peak PV energy production and efficient power delivery to laboratory loads under various conditions. This research introduces an advanced solution to recurrent power outage challenges in laboratory settings, offering a reliable and renewable power source for a more sustainable and resilient electrical infrastructure.

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1. INTRODUCTION

As the demand for sustainable energy solutions rises, the integration of photovoltaic (PV) systems emerges as an appealing option for powering machine laboratories. This study focuses on the intricate interplay of components within a renewable PV power supply system, emphasizing the utilization of solar energy through control mechanisms. The ever-increasing global energy demand, driven by population growth and industrial advancements, underscores the imperative of sustainable alternatives [1]. Renewable energy sources have emerged as a key solution to address this challenge, with a focus on power generation from renewable sources gaining substantial attention in recent decades. The concept of microgrids, characterized by integrated distributed generators like solar, wind, and diesel generators, along with energy storage systems and diverse loads, has gained prominence [2]. Microgrids operate in two modes: networked mode and islanded mode [3, 4]. While solar power generation is promising, particularly in island mode operation, it faces challenges due to natural variability and production uncertainties, making it inadequate for providing stable grid power [3-5]. To mitigate these issues, a hybrid approach is needed, combining solar energy with stable distributed sources like diesel generators and energy storage systems, supported by intelligent power management controllers [6-8]. Solar energy can fulfill daily energy needs during daylight hours, but nighttime demand necessitates energy storage solutions. Total solar irradiance, influenced by factors such as time of day, location, season, and weather conditions, makes a one-size-fits-all stand-alone solar system design impractical [9, 10]. Location specificity is a crucial aspect influencing PV power system design [11]. Furthermore, an instereting topology is proposed in [12] with the help of using PV-Battery-Supercapacitor system. Similarly, to exploit more wide-scale utilization of renewable energy sources, a standalone PV supported hybrid power system has been installed for an education and research laboratory [13].

In this paper, we present the design of a PV grid system, a promising means to achieve cost-effective electricity generation for a 25 kW load group. This system is grid-connected as a solar PV plant, efficiently harnessing maximum production capacity. Our objectives encompass evaluating the potential of a solar PV system, meeting laboratory energy needs efficiently, and promoting the integration of solar energy into our daily lives.

This study is organized into several key parts: Firstly, we explore the generation of electrical energy using solar panels. Secondly, we elucidate the controlling of the generation power, which is managed through the implementation of a DC-DC boost converter along with the maximum power point tracking (MPPT) algorithm, optimizing power output. Moving on to the third part, we discuss the conversion of DC current to AC current, facilitated by a three-phase inverter. The fourth part introduces the various

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electrical machines present in the electrical laboratory. The final section outlines the design of our integrated system, studied on the MATLAB/Simulink environment for simulation purposes, anticipating results related to voltage, current, power, speed, and torque.

2. RENEWABLE PHOTOVOLTAIC POWER SUPPLY SYSTEM FOR A MACHINE LABORATORY

A renewable PV power supply system offers an ideal solution for energizing a machine laboratory. This system operates by capturing energy from the sun and converting it into direct current (DC) electricity. In this study, we utilize a critical control component known as MPPT for the PV system. The MPPT's operation links on the recognition that a solar panel's power output varies with changing environmental conditions, such as sunlight intensity, temperature, and shading. In essence, a solar system taps into solar energy, transforming it into usable electricity capable of powering our machine laboratory. The quantity of electricity produced depends on various factors, including the size of the solar panels, sunlight exposure, and the efficiency of system components. It is important to mention that it is explored these aspects through simulations conducted using MATLAB/Simulink software. As depicted in Figure 1, the system comprises a PV array, a DC-DC boost converter controlled through "disturbance and monitoring" of MPPT, a three-phase H-bridge DC to AC inverter governed by pulse-width modulation for sinusoidal output, a three-phase LC filter, and an array of electric machines and generators earmarked for laboratory use.

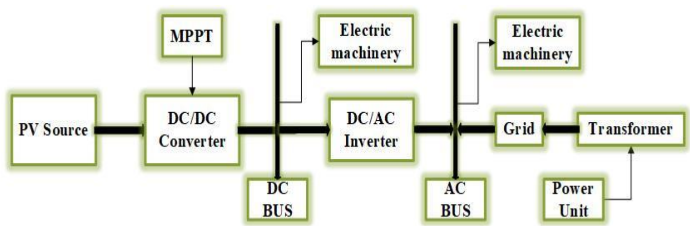

Fig. 1. Block diagram of proposed system (25 kW - 400V).

3. PHOTOVOLTAIC ENERGY CONVERSION SYSTEM

PV power generation is a process in which sunlight is converted into energy through the use of PV conversion cells. This type of renewable energy has gained great popularity due to its environmental benefits and low costs. In this study, it is employed Sun Power SPR 315E-WHT-D panel [14], organized into an array of 80 modules, as can be seen in Table 1. These modules are connected in four series-connected units for each series and 20 units in parallel. Each unit has a maximum capacity of 315 W, with a corresponding voltage rating of 54.7 V and a current rating of 5.76 A. The total maximum array power output is 25 kW, with a peak voltage of 218.8 V and a maximum current of 115.2 A. Figure 2 illustrates the voltage and current of the PV array. Each radiance and temperature value results in a distinct V-I function, as depicted in the scheme The variations in climatic conditions lead to changes in power, emphasizing the need for a converter with control. This is crucial to ensure that the PV generator operates at the optimal point, independent of climate and transitional conditions. In this scenario, the DC-DC boost converter is adopted to attain a stable DC voltage at the DC bus.

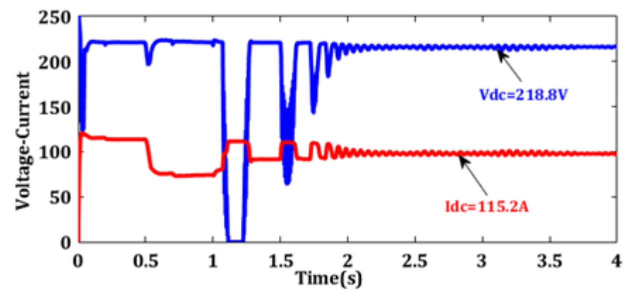

Fig. 2. The voltage-V_{DC} and current-I_{DC} of PV array.

Table 1. The parameters of the studied PV panel.

Parameter	*Value*
Maximum Power (P_{MAX})	315 W
Module Type	Sun Power SPR 315E-WHT-D
Voltage at Maximum Power (V_{MP})	54.7 V
Current at Maximum Power (I_{MP})	5.76 A

4. POWER ELECTRONICS CONVERTERS AND SYSTEM CONTROLLER

Power electronics play a critical role in PV systems and have several important functions, such as energy storage and transfer, which are also considered essential components to ensure the reliable, efficient, and effective operation of photovoltaic systems.

DC-DC Boost converter is an electrical circuit widely used in solar energy systems. This converter is designed to boost the low-voltage DC generated by PV panels. This improves energy efficiency by enabling the panels to operate at their maximum power point. MPPT controllers are designed to ensure that the energy obtained from solar panels is used with maximum efficiency [15]. These controllers continuously monitor the output voltage of the panels and adapt to changing conditions, allowing the panels to operate at the maximum power point. When these two technologies come together, the performance of solar energy systems increases significantly and can be adapted to various climatic conditions.

4.1. DC-DC Boost Converter and MPPT Controller

The backbone of the study lies in the deployment of the sophisticated MPPT algorithm within the PV system. MPPT plays a vital role in dynamically adjusting the operating point of solar panels to achieve maximum power output. It accomplishes this by continuously monitoring and responding to variations in environmental factors, such as sunlight intensity, temperature fluctuations, and shading effects. The algorithm ensures that the PV system operates at its peak efficiency, extracting the maximum available power under diverse conditions. The MPPT algorithm works to ensure the compliance of the system by continuing its operation at or near the MPP, through direct contact with a DC-DC converter, where control signals are sent to raise or lower the voltage according to the system's need [16]. Two popular MPPT algorithms for PV applications are easy to implement, perturb and observe (P&O) and incremental conductance (IC) algorithms, optimized using fuzzy logic controller (FLC) [17], this study has been implemented through

P&O algorithm as [18, 19]. One of the most important benefits of applying the MMPT algorithm is improving the efficiency of solar panels by up to 30%. Besides, a model of the PV modules, to analyze it's the electrical power generation is crucial [20]. This means that solar panels can generate more power, even in less-than-ideal environmental conditions, which in turn can help increase the overall performance of the solar system and reduce energy costs. The structure shown in Figure 3 represents the electrical circuit of the DC-DC boost converter that we adopted in our work. the developed model can be presented in Equation (1) and (2).

$$D = 1 - \frac{V_{in}}{V_{out}} \quad (1)$$

Where, V_{in} is the input voltage, V_{out} is the output voltage, and D is the duty cycle.

$$C = \frac{I_0 D}{f_S \Delta V_{out}} \quad (2)$$

Where, C is base capacitance, I_o is the output current, and f_s is the switching frequency, so the value of the inductor (L) can be expressed as below;

$$L = \frac{V_{out}}{6 f_S \Delta I_0} \quad (3)$$

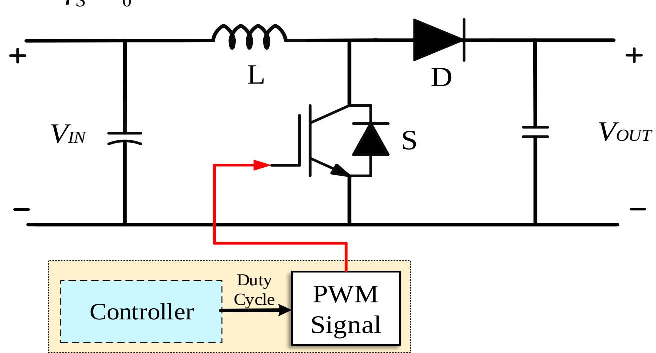

Fig. 3. Equivalent electric circuit of the DC-DC boost converter.

As shown in Figure 3 the process of energy absorption and injection in a boost converter is performed by a combination of four components which are the inductor, electronic switch, diode, and output capacitor. The principle of operation of the boost converter is based on the switching state. If the switch is off, the inductor stores energy and the capacitor supplies power to the load. If the switch is opened, the previously accumulated energy is transferred to the capacitor. Changing climatic conditions means varying the output voltage of the panel, which removes the voltage of the solar panels from the optimum value [19].

4.2. DC-AC Inverter with RC filter

One of the most important elements of this study is the three-level bridge that works as a three-level inverter, which is an electronic converter used in PV systems for the basic act of converting the DC output of the PV panel into AC power that can be used in the electrical network. It consists of four keys: two upper keys and two lower keys. Each switch is a semiconductor device such as an insulated gate bipolar transistor (IGBT) or a metal-oxide-semiconductor field-effect transistor (MOSFET) [21]. The PV panel generates a DC voltage connected to the DC bus of the three-level bridge. The DC bus is then connected to the upper and lower switches of the bridge. The switches are controlled by a pulse width modulation (PWM) signal generated by the controller. The PWM signal controls the switching of the upper and lower switches, allowing the DC voltage to be converted into a three-level AC voltage [22]. The voltage is then filtered using a device called an output filter and here we use an RC filter, which reduces high-frequency harmonics and generates pure sinusoidal AC voltage that connects to the electrical grid [13] as shown in Figure 4. The use of a filter is considered an important matter that helps improve the quality of the system and eliminate harmonic distortion in the output voltage, thus reducing electromagnetic interference (EMI) and improving efficiency.

The cut-off frequency of the filter is related to the values of the resistor and capacitor used in the filter. The cut-off frequency is the frequency at which the filter begins to attenuate the input signal and can be calculated by the following equation:

$$F_C = \frac{1}{2\Pi RC} \quad (4)$$

Where, F_c cut-off frequency, R and C is the impedance and capacitance respectively.

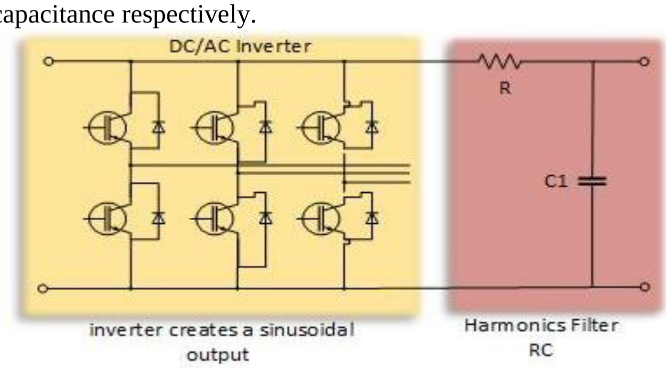

Fig. 4. Three-phase inverter topology with an output filter.

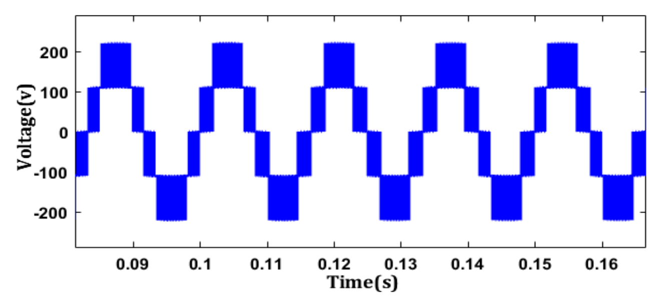

Fig. 5. The output voltage of the AC inverter.

The inverter system became modeled primarily based on the grid parameters with a three-phase model including six IGBT switches controlled by a bipolar PWM scheme. The inverter input is a rather constant DC voltage supply. The output voltage of the AC inverter can be seen in Figure 5. The input to the PWM is the output of the cascade manipulate unit, that is the demand voltage waveforms produced with the aid of the PI controllers from the generated error signal.

5. DESCRIPTION OF LABORATORY SIDE

This study involved the application of a group of electrical machines in an electrical laboratory, comprising various types. These machines are generally classified into DC machines and AC machines, and the overview of the study is summarized in Figure 6. The subsequent part of the study focuses on how solar energy can be utilized to operate such machines.

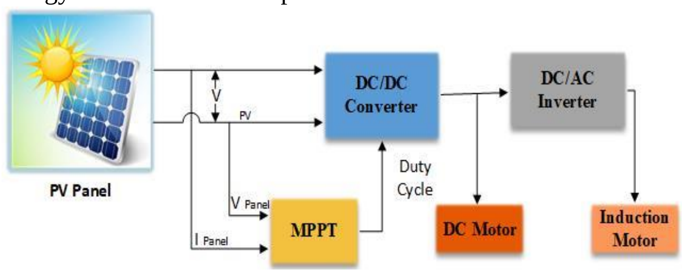

Fig. 6. Description of proposed system.

5.1. *Induction Motor*

Operating as the central component in our system's machine laboratory, the induction motor (IM) undertakes the primary responsibility of driving a mechanical load. Its pivotal role involves converting electrical energy harnessed from the renewable solar power system, constituting the power supply system, into mechanical shaft power. This mechanical power, in turn, fuels the operation of the machinery and apparatus within the laboratory. The connection of the PV system and IM is shown in Figure 6 and its simulation diagram is shown in Figure 7.

The IM exhibits a broad spectrum of power ratings and typically maintains a constant speed until reaching full load, its speed contingent on the frequency of the power source [23]. Power is supplied to the motor directly from a three-phase DC/AC inverter. This inverter plays a crucial role by converting DC into AC, facilitating the operation of electrical devices in the laboratory requires AC current, such as the IM [24].

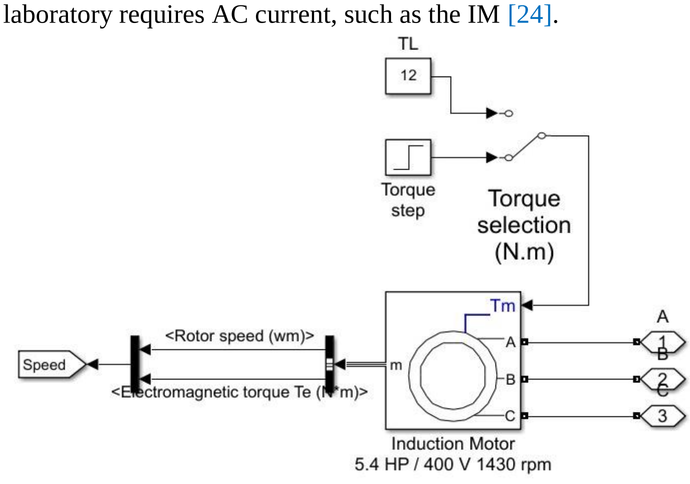

Fig. 7. The design and simulation of the IM.

Through the electrical circuit of the motor, we will use the prevailing data to set up the primary equations for voltage, and torque. In Figure 7, the desing created in MATLAB/Simulink environment illustrates the IM along with the fundamental equations governing its speed and induced torque. in Equation (5) and (6), we mention dynamic equations of the stator and rotor voltage, which are related to current and flux linkages.

$$\left.\begin{aligned} V_{s(a,b,c)}(t) &= R_{s(a,b,c)} i_{s(a,b,c)}(t) + \frac{d\Psi_{s(a,b,c)}(t)}{dt} \\ V_{r(a,b,c)}(t) &= R_{r(a,b,c)} i_{r(a,b,c)}(t) + \frac{d\Psi_{r(a,b,c)}(t)}{dt} \end{aligned}\right\} \tag{5}$$

$$T_e = J\frac{d\omega}{dt} + B\omega + T_L \tag{6}$$

In Equation (5), the first line is about stator parts whereas the second line is related to rotor parts. V, R, Ψ and i are the voltage, resistance, flux, and current of the motor. Where T_L is the load torque, J is the total moment of inertia, B is the viscous friction coefficient and ω is the mechanical angular velocity in Equation (6). The voltage applied to the stator windings dependent on the resistance, current flow, flux, and the torque applied on the rotor due to the stator rotating magnetic field expressed by T_e.

5.2. *DC Motors*

Another important device presented in this study is a DC motor, as its presence includes various applications within the PV system. The following is a description of how to integrate a DC motor into this system. Adding a DC motor on the DC bus side means connecting the DC motor to the same DC electrical system used in PV panels and DC-DC converters.

The use of a DC motor in such studies is considered a valuable educational and research tool, as it includes operations for DC motors and renewable energy systems. Also, controlling its speed and torque is considered simple and easy and depends on experiments and demonstrations that are conducted, whether in an electrical laboratory or in other industrial and practical applications. The connection of the PV system and DC motor is shown in Figure 6 and its simulation diagram shown in Figure 8.

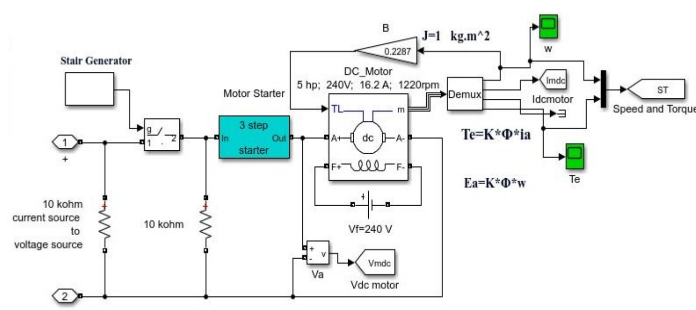

Fig. 8. Simulation model for DC motor.

Dynamic equations associated with the studied Simulink DC motor main equations are given as follows;

$$\left.\begin{aligned} V_f &= i_f R_f + L_f \frac{di_f}{dt} \\ V_a &= E_a + L_a \frac{di_a}{dt} + R_a i_a \end{aligned}\right\} \tag{7}$$

$$T_e = J\frac{d\omega}{dt} + B\omega + T_L \tag{8}$$

Where, V_f, L_f, i_f and R_f are field voltage, inductance, current and resistance respectively V_a, E_a, L_a, i_a and R_a are voltage, back electromotive force (EMF), inductance, current and resistance of armature respectively. The field voltage represents the applied voltage to the field winding, creating a magnetic field that interacts with the armature current to generate torque. In general, the torque equation is the same as that of the IM, but the motor's electromagnetic torque T_e varies depending on the type of motor. The presence of inductance in the armature influences the motor's time constant. Notably, the simulated design has been employed for convenient analysis of the torque equation and its variations, providing a computational tool for modeling and understanding the motor system's behavior.

6. SIMULATION RESULTS

The design of the electrical machine's laboratory is based on PV solar energy and is simulated using MATLAB/Simulink environment with the objective of the control of the powers. We used the MPPT technique with a boost converter controller, and here are the results of the simulated controller.

Examining Figure 9 reveals that solar irradiance fluctuates with the voltage of the solar cell. By referring to Figure 10, it becomes apparent that employing the MPPT algorithm results in reaching the maximum power point under varying weather conditions. This signifies that climatic conditions play a significant role in impacting the efficiency of solar cells.

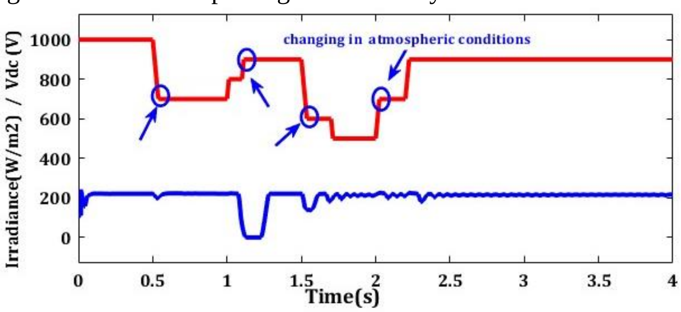

Fig. 9. The curve of the output voltage-V_{dc} (blue) driven by the PV array in changing atmospheric conditions regarding irradiance (red).

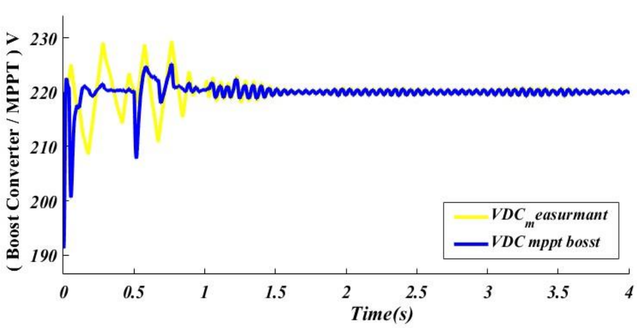

Fig. 10. DC-DC boost voltage output curve and performance of MPPT controller.

Figure 11 illustrates the maximum output power of PV panels. The MPPT algorithm adjusts the voltage of the solar panel to the optimum value. This adjustment is achieved by monitoring voltage and current values, and comparing them until the optimum point is reached. This point corresponds to the maximum energy production, considering changes in solar radiation and temperature. The algorithm maintains the highest system efficiency by increasing energy production.

Figure 11 displays the algorithm's performance after implementing the MATLAB simulation to achieve the maximum possible generated power. The application of the studied PV system was carried out on electrical machines. In the application part of the PV simulation in MATLAB, the operating characteristics of the speed and torque values of the motors used in the electrical laboratory have been obtained successfully.

Figure 12 shows that the maximum torque value is at startup when the speed is close to zero, and then it begins to decrease gradually until approaches nominal speed and stabilizes. This indicates that the motor could provide relatively proportional torque at speeds less than synchronous, therefore, as we can see the speed value of the motor is 154 rad/s, which is equivalent to 1471 rpm (also quite well), and the torque value is equal to 13.07 N.m.

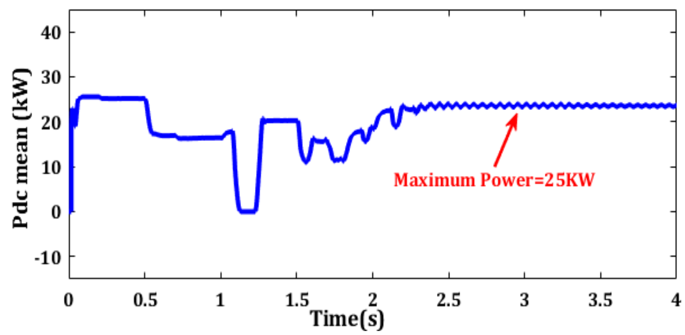

Fig. 11. The maximum output power of the PV panels.

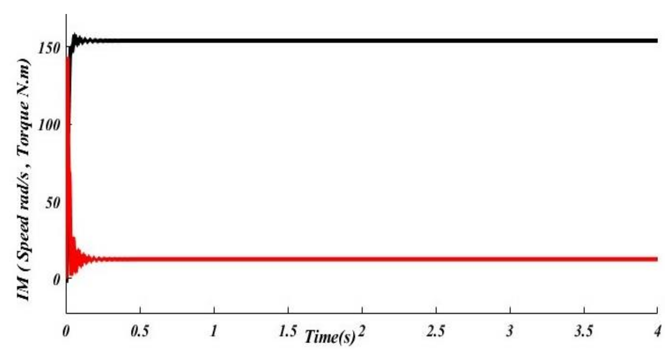

Fig. 12. Speed (black) and torque (red) of the IM.

As a result of controlling the speed of the DC motor, it has been known that speed control depends on the change in varying the voltage applied to it. Increasing the voltage typically increases the speed, and reducing the voltage decreases the speed. Speed control can also be achieved by using external control circuits or motor controllers.

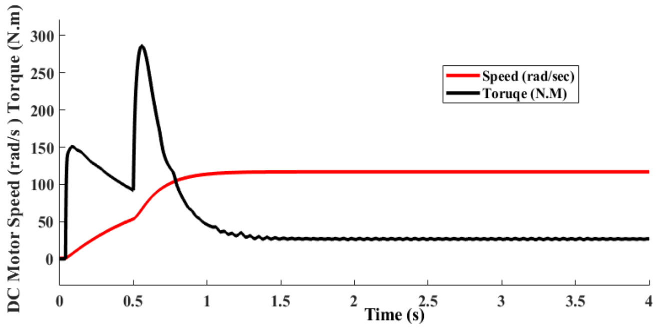

Fig. 13. Speed (red) and torque (black) values of the DC motor.

In Figure 13, the value of the DC motor speed is equal to 116 rad/s which means that is equal to 1117 rpm, as for the torque of the motor, it depends mainly on the current of the motor as we can see in Figure 13, the torque value of the DC motor is equal to 26.65 N.m. These findings show us the nominal system operation and simulation's correctness.

7. CONCLUSION

This study presents the design and implementation of a PV network system, representing a crucial step toward sustainable energy applications. The emphasis is on outfitting an electrical machinery laboratory with a networked solar panel array capable of generating up to 25 kW of energy. The objective is to attain the maximum power output capacity successfully and meet the electrical needs of electric machines or loads at the desired value-time through the correct integration and utilization of PV panels. The desired results have been achieved effectively.

While acknowledging that the experimental results of the MPPT controller were simulated rather than physically realized, we underscore the significant potential of renewable PV systems to contribute to sustainable energy practices and reduce carbon footprint. Additionally, this study establishes a framework for synergy among engineering, energy management, and environmental management. It serves as a blueprint for seamlessly integrating renewable energy systems into various industrial and educational contexts. Moreover, it provides a valuable resource to empower researchers, engineers, and individuals interested in the field of electrical and electronics engineering. It lays a solid foundation for sustainable energy supply and management, demonstrating the capability of renewable PV energy supply systems to meet the energy demands of industrial environments while also reducing environmental impact.

Nomenclature

T_e : Induced torque (N.m)
T_L : Load torque (N.m)
L_f : Field inductance (H)
R_f : Field resistance (Ω)
V_a : Armature voltage (V)
E_a : Back electromotive force (EMF)
L_a : Armature inductance (A)
Ψ : The permanent magnetic flux (Weber)
F_s : Switching frequency (Hz)
V_{out} : Output voltage (V)
V_{in} : Input voltage (V)
D : Duty cycle
I_{MP} : Current at maximum power (A)
L_s : Stator inductance (H)
J : Inertia moment
B : Viscous friction coefficient (Nm.s/rad)
F_c : Cutoff frequency (Hz)
C : Capacitive (F)
I_a : Armature current (A)
I_f : Field current (A)
R_a : Armature resistance (Ω)
ω : Angular speed (rad/sec)
I_o : Output current (A)
P_{max} : Maximum power (W)
V_f : Field voltage (V)
R_s : Stator resistance (Ω)
V_{MP} : Voltage at maximum power (V)
V_s : Stator voltage (V)

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