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# The Impact of Photovoltaic Systems on the Performance of Induction Motor in Agricultural Irrigation Applications

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***Abstract*—Water is a vital resource in the agricultural sector, as most farmland relies on tubewells for irrigation. Solar photovoltaic pumping systems (SPVPS) have emerged as a promising solution for sustainable agricultural irrigation, providing clean and efficient alternatives to traditional energy sources. However, induction motors used in (SPVPS) suffer from problems including voltage instability, decreased efficiency, overheating, and mechanical stress due to the varying nature of PV electricity. This paper focuses on the analysis of an irrigation system by MATLAB/Simulink simulation environment to analyze the performance of (SPVWPS), which consists of a 22 kW three-phase induction motor connected to a photovoltaic system under the climatic operating conditions of Mosul, Iraq. The results showed that operating the water pump using the solar system led to a decrease in the motor torque by 9% and the motor efficiency decreased by 34.3% compared to when supplied with electrical power from the grid. The results showed that the system achieved its best performance at a peak of the solar irradiance of 860 W/m² and a temperature of 24.6°C, with the induction motor speed reaching 1,317 rpm and a maximum efficiency of 48.4%. The total harmonic distortion (THD) in the rotor current peaked at 184.37% at 24°C before decreasing to approximately 45.3% at higher temperatures. The increased THD is due to a combination of inverter stress, poor waveform quality under thermal load, and high-frequency disturbances caused by variable environmental conditions. It's a typical challenge in solar-powered motor drives, especially in off-grid or remote agricultural systems. These results effectively contribute to supporting sustainable agricultural practices by ensuring the continuity and efficiency of motor operation.**

***Keywords—Solar Water Pumping; PV Panels; Agricultural Technology; Induction Motor; Agricultural Photovoltaic; Stand-alone PV System.***

## I. Introduction

Integrating photovoltaic (PV) systems contributes to enhancing the efficiency of agricultural irrigation systems by providing a reliable and sustainable source of energy to operate pumps and equipment. This integration reduces reliance on fossil fuels, lowering operating costs and carbon emissions. It also enhances the sustainability of the agricultural sector, especially in rural areas with poor electrical infrastructure [1]–[6]. Solar water pumping stations (SWPPs) are among the most important and promising applications of photovoltaic systems in all of the above areas. Advances in photovoltaic modules, in terms of production, design quality, and the technologies used in these systems, have made them among the most suitable and widely used water pumping systems [7]–[11].

These systems use solar energy to lower expenses and increase operational efficiency in addition to offering a sustainable power source [12]–[16].

Although the on-grid power supply provides the necessary power for an irrigation pump motor, there are still concerns about the availability of electricity in rural locations. Choosing clean and green energy is essential to living a self-sustainable life in light of growing worries about global warming and carbon [17]–[20] and water is becoming increasingly crucial for urban areas, agriculture, and the world's expanding population, especially in emerging nations. Securing access to water sources in rural or remote areas requires the provision of efficient pumping technologies supported by adequate and sustainable energy systems to ensure the continuous and reliable operation of water systems in light of the limitations of traditional infrastructure [21]–[24].

One of the most vital components of the global food supply is agricultural irrigation, especially in arid regions. This is due to the environmental and financial challenges faced by irrigation systems powered by conventional energy sources. Clean energy generated from PV systems and directly from sunlight is one of the most important and largest clean energy sources and is considered a practical and environmentally friendly solution [25]–[33]. When PV systems are integrated into irrigation systems, farmers save significant energy costs. They also help save the environment by reducing pollution and greenhouse gases [18], [34], [35]. The 85% drop in the price of flat-panel solar panels over the past decade has led to a lower tariff, reaching €0.5/W. This has fueled the widespread and accelerated adoption of photovoltaic irrigation systems [2], [36].

Various types of electric motors have been used in irrigation systems. However, with the increasing use of solar energy in irrigation systems, several problems have emerged with these types of electric motors [5], [37]–[42]. In addition, there are numerous techniques and methods that were used to achieve the optimal practical environment for these types of motors when used in agricultural irrigation systems. Induction motors are widely used in agricultural irrigation systems because they are designed to operate efficiently with a constant power source [43]–[51].

Despite the advantages and benefits of PV irrigation systems and modern techniques, they also have drawbacks that can make operating water pumps and induction motors, commonly used in agricultural irrigation, difficult. Fluctuations in voltage and frequency, as well as varying radiation and temperature during operation. In addition to increased losses and total harmonic distortion for the voltage and current are among the most significant challenges facing these systems [52]–[55].

Undoubtedly, these variables will impact the performance of the induction motor, resulting in mechanical stress variations, decreased efficiency, increased harmonics, and increased temperature. Therefore, it is essential to know, interpret, and understand these variables between induction motors and solar energy systems used in irrigation systems [56]–[60]. However, due to the inherent characteristics of solar energy systems, these systems may not operate properly when operated and used in irrigation systems. Fluctuations in the aforementioned variables can lead to, first, a shortened motor lifespan and, second, a reduced efficiency, which can impact irrigation operations. Furthermore, a mismatch between PV output and motor operation, especially during critical times, can impair performance and increase energy losses [34], [61], [62].

This study aims to demonstrate the importance of using solar energy systems in irrigation systems, as well as the impact of voltage and frequency fluctuations from these systems on induction motors used in such systems. The study also addresses the key elements that can affect the characteristics of an induction motor. Field experimental results were taken from field irrigation systems in Mosul, Iraq, to highlight these points and problems that should be addressed by specialists and consultants in this field. A solar photovoltaic water pumping system (SPVWPS) was designed, taking into account water requirements, solar radiation resources, and the optimal tilt angle and orientation of the panels. The MATLAB/Simulink simulation environment was used to analyze the performance of the designed system. This paper focuses on the analysis of an irrigation system consisting of a 22 kW three-phase induction motor connected to a solar photovoltaic system under the climatic operating conditions of Mosul, Iraq. This study will provide a clear, evidence-based vision to ensure improved performance of motors used in irrigation systems.

## II. Materials and Methods

In order to determine the crucial elements influencing the induction motor's performance, the simulation data are lastly examined. To evaluate the effects of temperature, motor load, and solar irradiation on motor behavior, parametric tests are carried out. The results shed light on the difficulties faced by PV-fed systems and aid in the suggestion of fixes to raise motor efficiency and stability [63]–[66]. The study gains from a flexible platform that can model complex systems and analyze their interactions in an affordable and tightly controlled virtual environment by relying just on MATLAB/Simulink [67]–[69], [69]–[73]. The proposed methodology in this study, dependent on the scalar control technique to operate a solar water pump, can be illustrated in the flow chart shown in Fig. 1. The water pump is controlled by an induction motor powered by SPWM technology. The motor requires controlling the voltage and frequency to achieve a constant flow rate. The reference speed is the input parameter upon which this control technique will be based, and it depends on the electrical power generated by the photovoltaic array, which in turn depends on weather conditions (irradiance intensity and temperature).

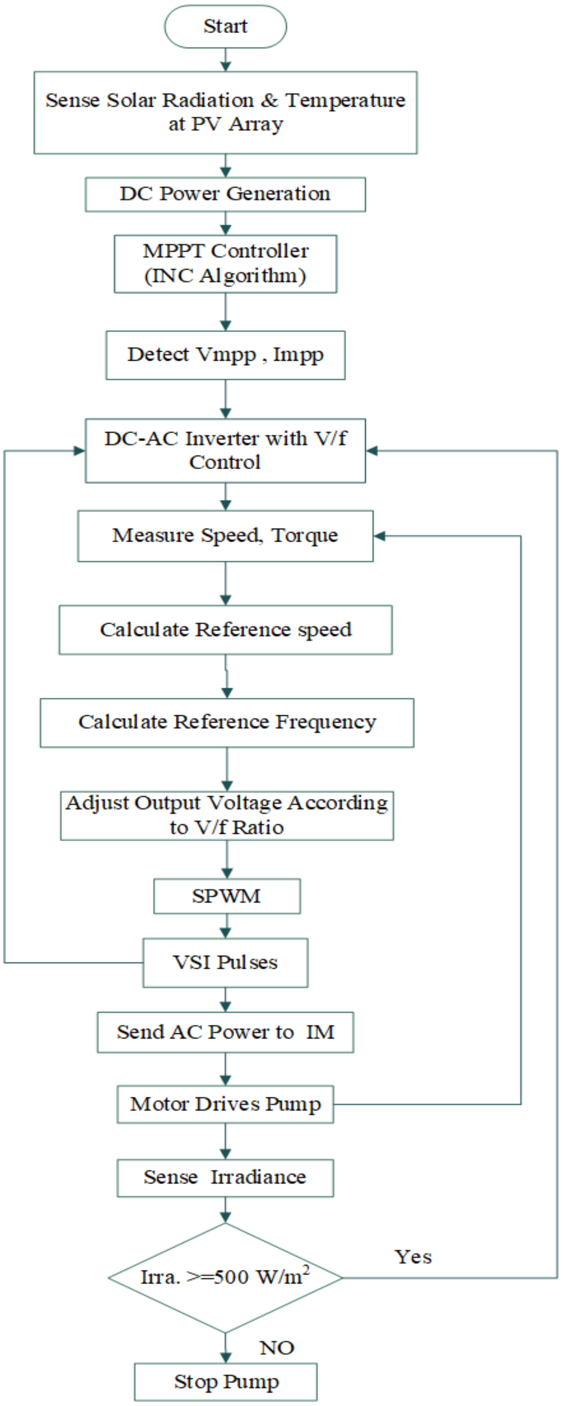


Fig. 1. Proposed methodology flow chart

The photovoltaic water pumping system shown in Fig. 2 consists of a photovoltaic array followed by a boost converter that extracts maximum electrical power from the photovoltaic array using the incremental conductance method under various weather conditions. A V/f controller is also used to control the IM. A VSI is used to provide pulse-width modulated voltage input to the motor and pump assembly.


Fig. 2. Components of PV water pumping system

### A. Pump Water Selection

An induction motor of 30 HP (22kW) is selected for the proposed system. The motor pump parameter and specifications are shown in Table I.

TABLE I. MOTOR PUMP SPECIFICATIONS

| Description | Specification |
|---|---|
| MODEL | Y2-1180L-4 |
| Voltage (V) | 380 |
| Number of poles | 4 |
| Power | 30 HP (22 kW) |
| Speed (rpm) | 1470 |
| Current (A) | 43.2 |
| Efficiency % | 91 |
| Torque (N.m) | 142.93 |
| Moment of Inertia (kg·m$^2$) | 0.102 |
| Power factor | 0.85 |

The power consumption of a water pump is directly proportional to the cube of its rotational speed. The pump proportionality constant ($K_{Pump}$) is derived based on the rated power of the motor and its rated rotational speed, as shown in Equation (1).

$$Pump\ Constant\ (K_{Pump}) = \frac{Motor\ Rating\ (P)}{(2\pi * Motor\ Rating\ Speed\ /60)^3} \quad (1)$$

### B. Design of Solar PV Array

When designing a solar PV system for standalone operation, one important consideration is the safety factor, a multiplier that takes into account the size of the system components to accommodate sudden voltage fluctuations, temperature changes, and increased loads in the future.

In addition, the array capacity must be compatible with the inverter size. In this case, a PV array is selected as 38 kW in which 66 PV modules type (LONGi LR5-72HGD-585M) are used. The PV array consists of 11 series modules in the string with 6 strings connected in parallel. The individual module specifications are provided in Table II.

TABLE II. PV MODULE SPECIFICATIONS

| Parameter | Value |
|---|---|
| Maximum Power | 585 W |
| Voltage at Maximum Power | 43.33 V |
| Current at Maximum Power | 13.51 A |
| Open Circuit Voltage | 51.52 V |
| Short Circuit Current | 14.30 A |
| Temperature Coefficient of Voc | -0.23 %/oC |
| Temperature Coefficient of Isc | +0.045 %/oC |
| Cell Number | 144 |

In this study, the effect of daily weather conditions (Solar radiation and temperature) in the city of Mosul in Iraq during April was demonstrated. This irrigation system was used for six hours, extending from 7:00 AM to 1:00 PM, as shown in Fig. 3. This data was used as inputs to a signal Editor block that is connected to the PV array inputs.

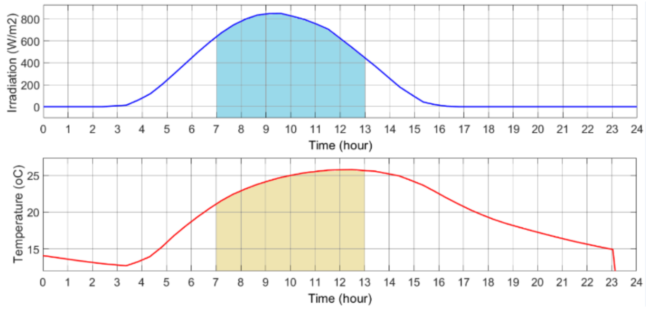


Fig. 3. Irradiance and temperature curves on 1 April in Mosul City, Iraq

Fig. 4, shows the (I-V) and (P-V) characteristics of the proposed photovoltaic array model at different solar radiation and a temperature of 25°C. The radiation ratio and temperature play an important role in predicting the (I-V) characteristics, and the effects of both factors must be taken into account during the design of the photovoltaic system.

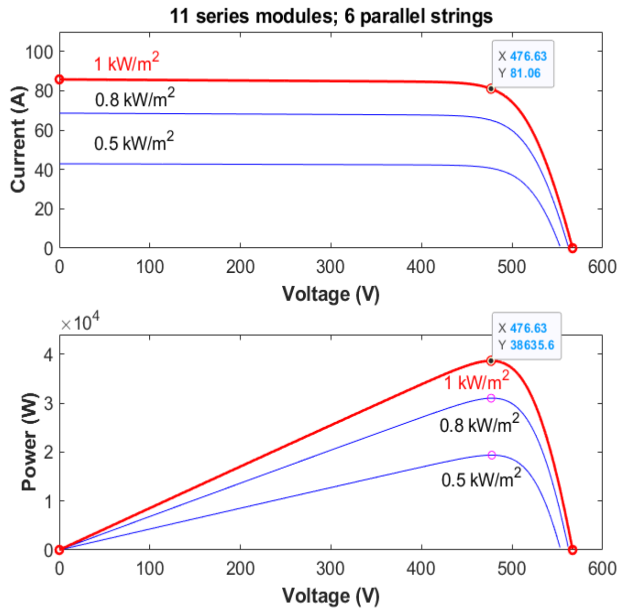


Fig. 4. (I-V) and (P-V) characteristics of the designed PV array

### C. Design of DC-DC Boost Converter

The power converter is an essential component in photovoltaic (PV) systems. One type is the DC/DC boost converter, which is fed from the photovoltaic (PV) array, as shown in Fig. 5. The boost converter is a highly efficient electrical circuit used to raise the voltage from the PV array to the optimal operating voltage level, with the aim of achieving maximum power point tracking (MPPT). This type of converter has several advantages, including simplicity, low cost, high efficiency, and high reliability compared to other configurations.

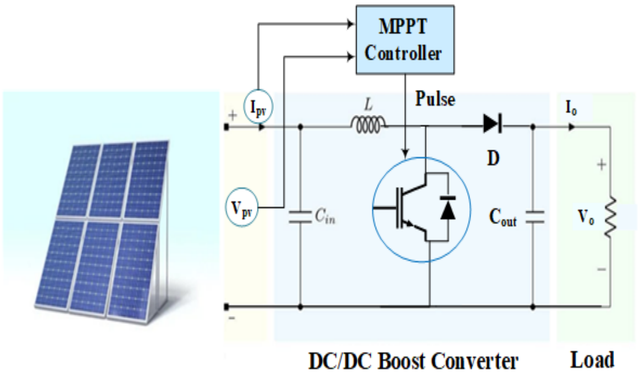


Fig. 5. Schematic of a DC-DC boost connected to a PV array

The boost inductor duty cycle, (D) is given as (2),

$$D = 1 - \frac{V_{PV,Mpp}}{V_O} \quad (2)$$

Thus, the Boost Inductance, L is calculated as (3),

$$L = \frac{D * V_{PV,Mpp}}{f_{sw} * \Delta I_L} \quad (3)$$

Where $V_O$ is the DC-Link Voltage, $V_{PV,Mpp}$ is the PV Array voltage at maximum power point, $f_{sw}$ is the switching frequency, $\Delta I_L$ is the amount of ripple current. The value of the Boost Inductance L is selected as 2 mH.

*1) Control of Boost Converter:* In this paper, the topology used is a two-stage conversion system for PV array-fed water pumping. This system embodies a standard control of induction motor operation and maximum power extraction from the PV array using an incremental conductance (INC) algorithm. The simplicity and ease of implementation of standard control outperform precision control algorithms, even if they require intensive calculations, such as vector control and direct torque control, the voltage and current of the photovoltaic array are sensed and fed into the (INC) algorithm. This algorithm determines the duty ratio of the boost converter based on changes in voltage, current, and power. A proportional-integral controller (PI) is used to maintain a constant voltage at the boost converter's output.

*2) MPPT ALGORITHM:* Due to the low operational efficiency of photovoltaic (PV) arrays, a maximum power point tracker (MPPT) is employed to enhance their effectiveness under variable irradiance and temperature conditions.

The incremental conductance algorithm is one of the most widely used in this field, due to its high accuracy and ability to adapt to year-round weather fluctuations [74]–[77]. This algorithm relies on measuring both the array's output voltage and current using voltage and current sensors, then calculating the instantaneous conductance and incremental conductance at two consecutive time points (k-1). The array terminal voltage is adjusted to meet the maximum power point tracking condition, which is expressed by the mathematical equation:

$$\frac{\Delta I_{PV}}{\Delta V_{PV}} = \frac{-I_{PV}}{V_{PV}}, \; at\ MPP \quad (4)$$

$$\frac{\Delta I_{PV}}{\Delta V_{PV}} > \frac{-I_{PV}}{V_{PV}}, \; at\ the\ left\ of\ MPP$$

$$\frac{\Delta I_{PV}}{\Delta V_{PV}} < \frac{-I_{PV}}{V_{PV}}, \; at\ the\ right\ of\ MPP$$

The duty ratio of the boost converter is adjusted by the algorithm as shown in Fig. 6,

The operation of the INC algorithm works by gradually connecting (ΔI/ΔV) of the P-V characteristics, detecting the slope of the P-V characteristics curve (ΔP/ΔV). The value of this slope is equal to zero at the MPP point. If the slope value is greater than zero, then it is on the left side of the MPP, and when it is less than zero, it is on the right side.

If the encountered slope is negative, the controller shifts the operating point to the left by decreasing the PV array voltage, and vice versa. This process continues until the slope becomes zero, indicating that the MPP has been reached.

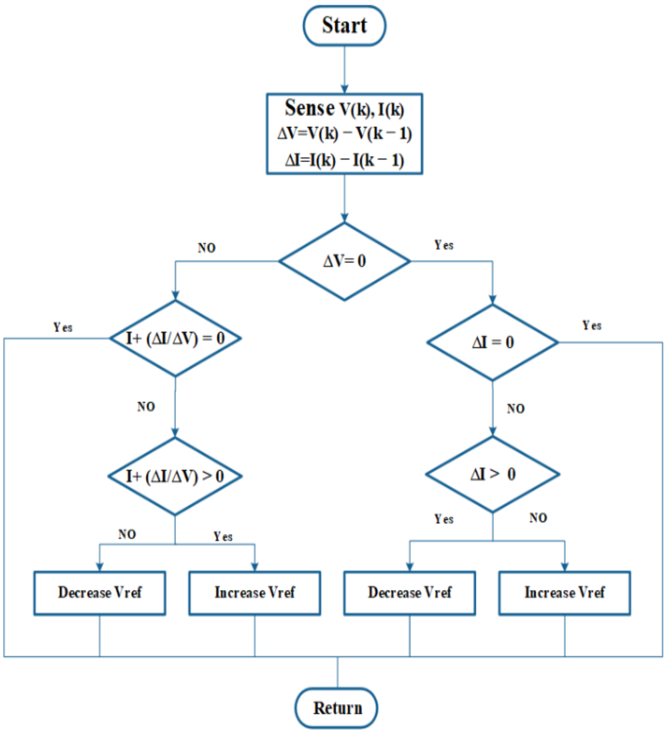


Fig. 6. Flowchart of (Incremental Conductance Algorithm)

## D. Scalar (V/F) Control of Pump Water Motor

Scalar control of three-phase induction motors is the most common type of control by far due to its simplicity. Induction motors are typically powered by a 50 Hz voltage source. To control the motor and maintain a constant flux, the voltage must be proportional to the frequency [78]–[80]. When the motor is operating at a lower speed, the voltage must be reduced. Therefore, the reference speed can be considered the input to the control mechanism of V/f as shown in Fig. 7. According to the centrifugal characteristics of the pump, load torque is related to the speed according to the (5),

$$T_L = K_{Pump} * \omega^2 \quad (5)$$

Where TL represent is the load torque of the water pump, $K_{pump}$ is the pump constant, and ω is the rotor rotational speed measure in rad/s.

So, the absorbed pump power $P_L$ and its speed are directly related as mentioned in (6).

$$P_L = K_{Pump} * \omega^3 \tag{6}$$

The power generated by the photovoltaic array is used to calculate the speed feed forward limit, in order to perfect the system dynamic performance.

$$\omega^* = \sqrt[3]{\frac{P_{PV}}{K_{Pump}}} \tag{7}$$

Then used this reference speed $\omega^*$ to estimate the required reference operating $f$ frequency.

$$f = p\frac{\omega^*}{2\pi} \tag{8}$$

Where $p$ is the number of the pole-pairs of the motor. The reference frequency $f^*$ can be calculated from (9),

$$f^* = f - \Delta f \tag{9}$$

$\Delta f$, obtained from the DC-link voltage error using PI controller. The term $\Delta f$ compensates for the motor losses to ensure a power balance over the DC-link capacitor.

The induction motor is controlled using the Scalar V/f control algorithm, which generates control pulses in VSI.

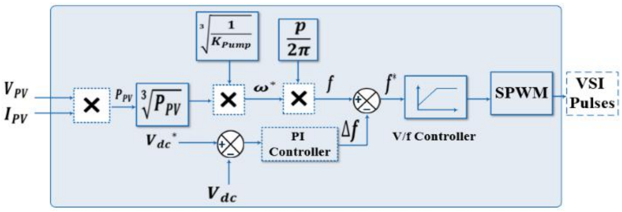


Fig. 7. The control scheme of the PV water pumping system

## III. Results and Discussions

The response to the suggested PV water pumping system is analyzed in MATLAB/SIMULINK as shown in Fig. 8. The IM operation is analyzed under various weather conditions to evaluate the dynamic response of the PV water pump.

The results were based on operating data in the computer simulation when the pump was powered directly from the electrical grid. The other part of the results, which is more important, is when the pump was powered by solar cells. To demonstrate the effect of photovoltaic systems on induction motor performance in agricultural irrigation applications, results were taken for both stator and rotor voltages and currents, as well as torque and speed. In addition, the results for efficiency and the resulting harmonics were analyzed, and their impact on the performance of these systems was demonstrated.

First, the motor's performance was demonstrated when powered by a photovoltaic (PV) system under standard test conditions (STC) (solar radiation of 1,000 W/m² and temperature of 25°C) compared to a conventional electrical grid, as shown below.

In Fig. 9, It is noticeable that the motor, when powered by the solar system, exhibits significant power fluctuations during the first seconds of operation, reflecting the difficulty in providing stable and responsive power. This behavior often results from the solar system's slow response to load changes or from fluctuating solar radiation, especially in the absence of backup batteries. Although the power stabilizes relatively at 1.9 kW after about two seconds, there are some momentary power drops at times 5, 6, and 7 seconds, indicating limited instantaneous power supply or a temporary deficit in the PV output.

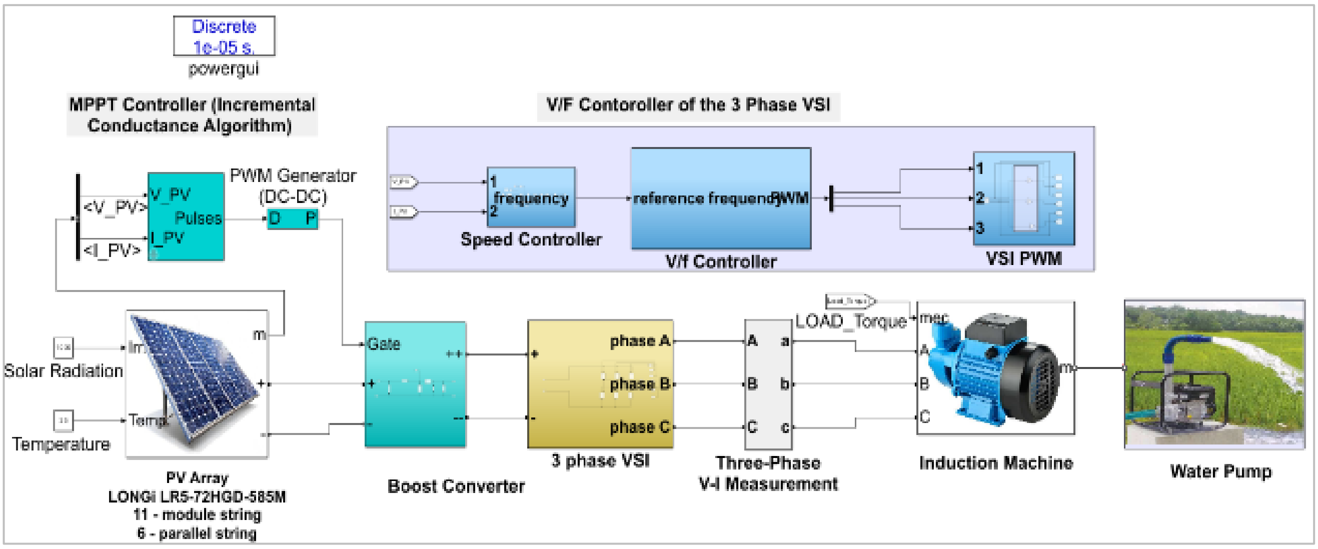


Fig. 8. Modeling the PV water pump system in MATLAB/SIMULINK

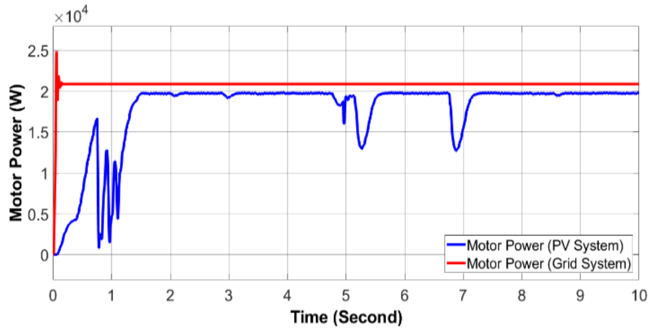


Fig. 9. IM power output in PV system and Grid system

In contrast, when powered by the electrical grid, the motor exhibits an immediate and stable response from the first moment, with nearly constant power at 22 kW throughout the entire operation period without any fluctuations. This reflects the high reliability of the grid in supplying dynamic loads. Therefore, powering motors from a solar system often requires additional support via energy storage systems or hybrid configurations such as PV-Grid to ensure operational stability, especially in applications that require high reliability when starting and withstanding sudden load changes.

While in Fig. 10, shows the motor speed in rpm versus time (in seconds), comparing the motor's performance when powered by a solar PV system versus the grid. It clearly shows a significant difference in speed behavior between the two systems.

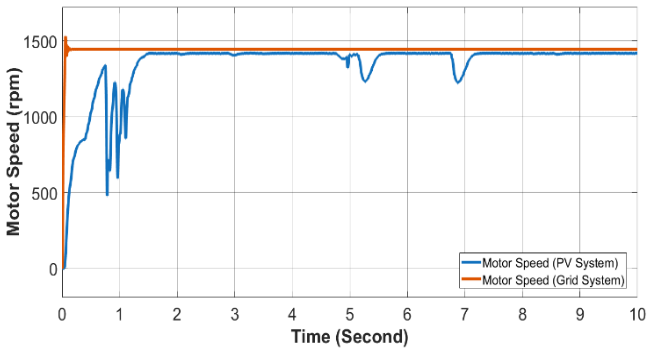


Fig. 10. IM speed output in PV system and Grid system

When the motor is powered by the solar system, it is noted that the motor speed initially (from 0 to approximately 2 seconds) experiences sharp fluctuations and significant instability due to insufficient instantaneous power or instability in the solar system's input voltage. Although the speed subsequently stabilizes at the nominal value (approximately 1450 rpm), there is a clear, temporary drop in speed at moments 5, 6, and 7 seconds, indicating fluctuations in the power supplied by the solar cell due to changes in irradiance or a delayed response from the power regulator (MPPT or inverter).

In dissimilarity, the grid exhibits remarkably stable performance, with the motor speed reaching the desired value immediately without fluctuations and remaining constant throughout the entire operating period (0–10 seconds). This reflects the grid's ability to supply the motor with stable and sufficient power, ensuring stable speed and high operational reliability.

Therefore, it can be argued that a solar system requires additional support (such as batteries or advanced regulation technologies) to ensure stable speed and reduce fluctuations, especially when operating dynamic loads such as motors. The electrical grid, however, remains the most stable option for operating motors in environments that require high reliability.

Fig. 11, compares the performance of an induction motor when powered by the grid versus when powered by a solar PV system. It is clear that when powered by the grid (red line), the motor maintains a nearly constant torque throughout its operation, indicating stable and consistent power supply from the grid without fluctuations that would affect the motor's performance. Looking at the graph from the perspective of system response and dynamic control, a clear difference can be observed between operating an induction motor from the grid and operating it from a solar PV system. When powered by the grid, the torque appears nearly constant from the moment of take-off, indicating an immediate response and a high ability to maintain the required torque without fluctuations, thanks to the high stability in voltage and frequency provided by the grid.

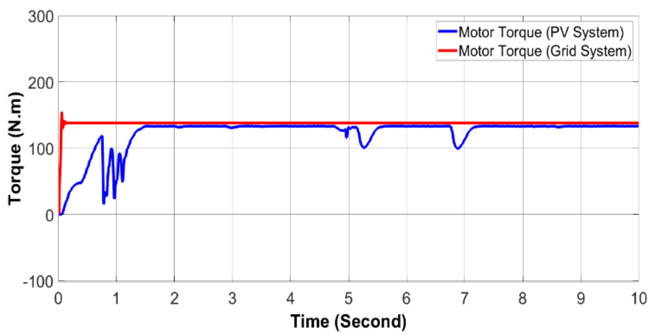


Fig. 11. IM Torque output in PV system and Grid system

In difference, when powered by a solar PV system, there are clear fluctuations at the start of operation and a gradual stabilization after a few seconds. This fluctuation may be due to the slow response of the power converters connected to the solar cells or to fluctuations in solar radiation that affect the continuity of the power supply. Some momentary drops in torque during operation also indicate that the solar system needs improved control or additional support through energy storage units. Therefore, it can be argued that operating the motor from the grid is more reliable and dynamically stable, while operating from solar cells requires supporting technical solutions to achieve a similar level of performance.

Fig. 12, shows the rotor currents of the induction motor quickly reaching a steady state after a short period of operation without significant fluctuations. This indicates that the electrical power supplied to this motor had a clear impact on performance due to the availability of constant voltage and current. This performance contributes to the stability of the irrigation system from the moment of startup.

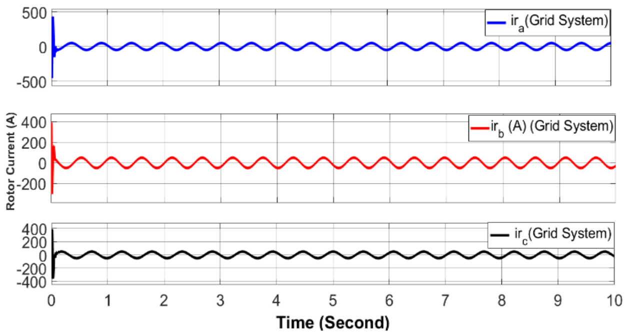


Fig. 12. Rotor current of IM in Grid system

The induction motor currents (three-phase rotor currents) can be seen in Fig. 13. It is clear that the fluctuations are high and that these currents are unstable during the first moment of startup. This situation is practically undesirable in such systems due to the difficulty of controlling the starting current of the three-phase induction motor. This indicates the difficulty the PV system is having providing a stable current during startup due to a delay in the stabilization of the output voltage or the response of the power converter. After this period, the current fluctuations begin to gradually decrease and stabilize significantly, while the natural fluctuations associated with motor operation under variable load conditions persist. This indicates that the solar array is capable of operating the motor efficiently after passing the startup phase. However, this requires a longer time to reach steady state compared to conventional sources, reflecting the need to improve control and rapid response technologies in PV systems to ensure more stable motor performance.

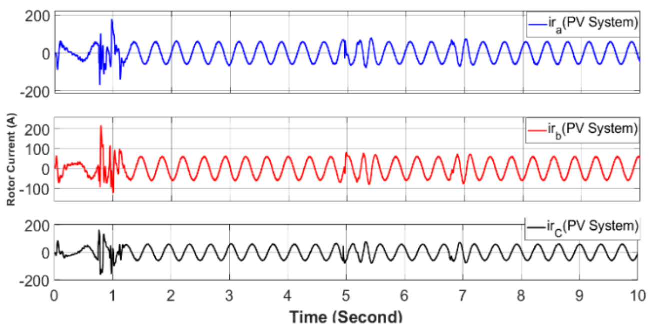


Fig. 13. Rotor current of IM in PV system

Fig. 14 and Fig. 15, show a comparison of the harmonic content of the rotor current of an induction motor when powered by the mains and a photovoltaic (PV) system, using frequency spectrum analysis and total harmonic distortion (THD) measurements. In the Fig. 14, the fundamental component at 50 Hz is clearly dominant, reaching a high value (350), while the amplitude of the higher harmonics gradually decreases in a systematic manner. The total harmonic distortion (THD) value at STC is approximately 21.91%, which is considered moderate and acceptable in many industrial applications and indicates relatively good motor current quality due to the stability of the voltage supplied from the mains.

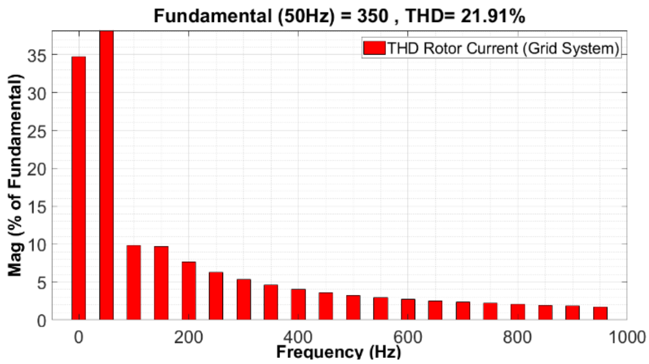


Fig. 14. THD in rotor current of IM in Grid system

While Fig. 15, the fundamental component is very weak (0.1289), while the harmonics are much more prominent and spread across a wide frequency range. The total harmonic distortion value is very high, reaching 132.63%, indicating a high percentage of harmonics and distortions in the current, which can negatively impact the motor's efficiency and operational life. This high distortion is often due to the characteristics of the power converters associated with the PV system, such as pulse modulation techniques or fluctuations in solar radiation, which lead to impure and irregular current.

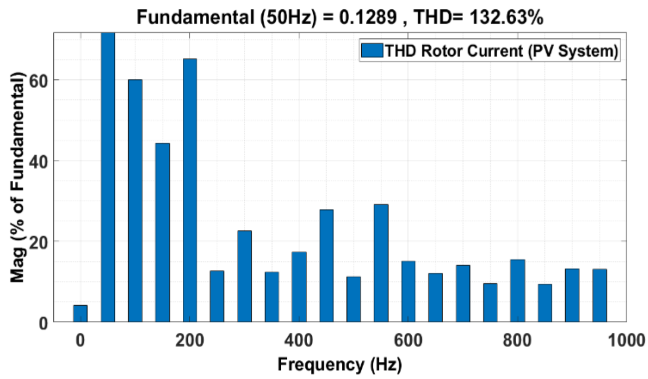


Fig. 15. THD in rotor current of IM in PV system

By comparison, it is clear that the electrical grid provides a purer current in terms of the frequency spectrum, which enhances the stable performance of the motor, while PV systems require improvements in filtering and control techniques to reduce harmonics and ensure better operation of the motors connected to them. Fig. 16 and Fig. 17 show a comparison of the frequency spectrum analysis of the stator current in an induction motor when operated from two different sources: the power grid and a photovoltaic (PV) system. In the Fig. 16 (the power grid), we notice that the fundamental frequency (50 Hz) is clearly visible and very high (377.6), reflecting the regularity and balance of the voltage and current supplied from the grid. The total harmonic distortion (THD) is 12.80%, a relatively low percentage that indicates that the current contains a small percentage of harmonics, which indicates high electrical quality and stable motor operation.

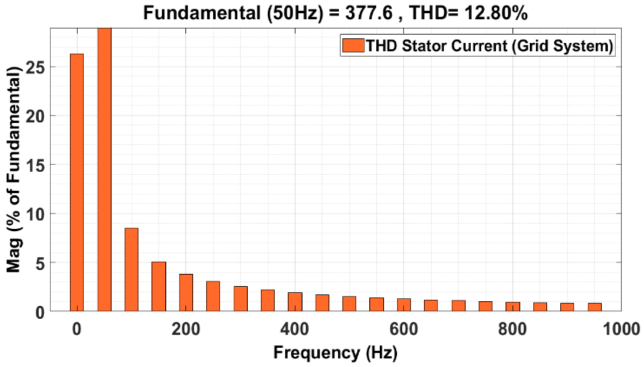


Fig. 16. THD in stator current of IM in Grid system

Fig. 17 (the PV system), we notice a significant difference. The fundamental frequency is very low (0.131), while the harmonics appear large and are distributed across a wide frequency range, indicating an irregularity in the resulting current. The total harmonic distortion (THD) in this case reaches 132.63%, a very high value indicating a high level of distortion in the stator current. This distortion may be due to the power conversion technologies associated with solar systems, such as inverters, which produce non-ideal waveforms.

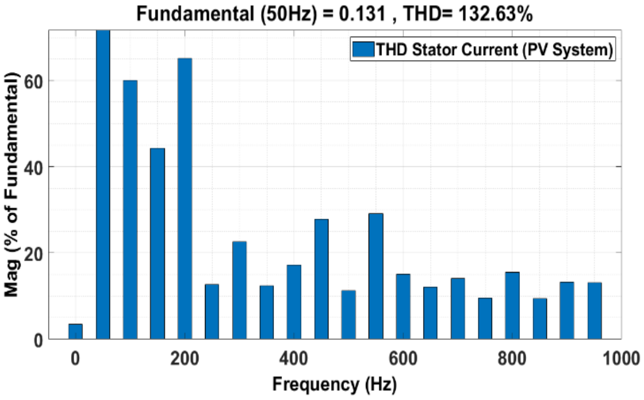


Fig. 17. THD in stator current of IM in PV system

In solar water pumping systems, the inverter introduces harmonics because it generates a non-sinusoidal waveform using PWM (Pulse Width Modulation). as well, Erratic switching due to rapid MPP tracking or unstable voltage causes more harmonic content in the stator voltage. As it is the rotor current (in a squirrel cage is especially sensitive to harmonics in the stator voltage/current.

Lead to distorted magnetic fields, especially at the air gap. This reflects in a distorted rotor current. May increase resistance, affecting current waveform shape and filtering, making harmonics worse. During peak radiation, irradiance can reach 1000 W/m².

Scientifically, this variation in current quality reflects the extent to which the power supply affects the performance of induction motors. Currents with high harmonics lead to additional losses in iron and copper and cause vibrations and excessive heat, reducing the efficiency and lifespan of the motor. Therefore, operating motors from the conventional grid is more suitable in terms of stability and accuracy, while operating them from PV systems requires the use of effective filters or advanced control technologies to reduce harmonics and improve the quality of the supplied power.

Fig. 18 illustrates the relationship between temperature, solar radiation, and the load power generated by a solar power system. Solar radiation primarily controls the power available to the motor—higher radiation improves output, while lower radiation reduces it. We observe that the load power gradually increases with increasing solar radiation, reaching a peak of approximately 15.8 kW at an irradiance of approximately 860 W/m². This behavior reflects the direct relationship between increased solar radiation and improved output, as long as the temperature remains within the appropriate limits.

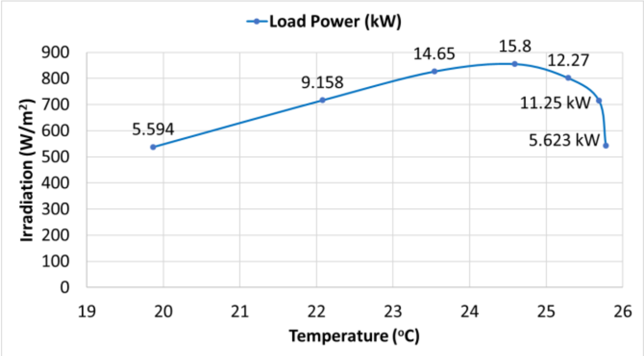


Fig. 18. IM power with variable weather conditions in PV system

It is well known that the efficiency of solar panels begins to decline with increasing temperatures. This occurs when temperatures exceed 25°C. However, when temperatures reached 25.5°C, a significant drop in power was observed, reaching 5,623 kW. Therefore, this highlights the importance of thermal control and optimizing ventilation systems in solar power systems to achieve optimal performance.

Fig. 19 shows that motor torque gradually increases with a significant increase in temperature. When the temperature rises from 20°C to 24°C, the maximum torque reaches 114.0 Nm. This behavior indicates that increasing solar radiation and rising temperature within the above range enhances the system's energy production. Consequently, motor power increases and overall efficiency improves.

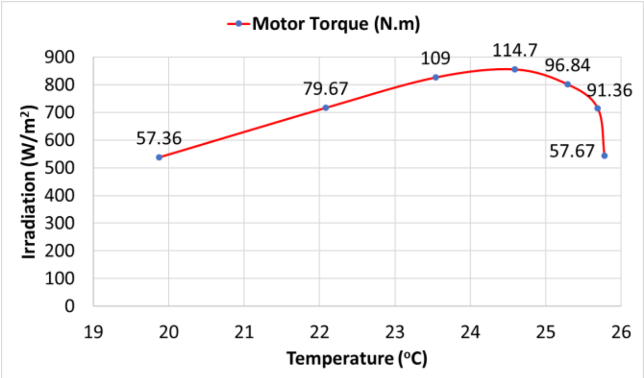


Fig. 19. IM Torque with variable weather conditions in PV system

However, after the decline of the irradiance and exceeding 24°C, motor torque gradually decreases despite the continued increase in temperature, reaching 57.67 Nm at 25.5°C. This behavior demonstrates that decreasing the irradiance leads to a decrease in the electrical output, and excessively high temperatures negatively impact the performance of the photovoltaic system and consequently a reduction in the torque generated, this is attributed to thermal losses and increased resistance in the electrical system components, highlighting the importance of controlling the operating temperature to maintain consistent motor performance.

Fig. 20 shows the relationship between temperature (°C) and solar radiation intensity (W/m$^2$), with motor speed (rpm) indicated at each data point. The curve shows a nonlinear relationship between temperature and radiation, with radiation intensity increasing as temperature rises up to a certain point, then decreasing as the temperature continues to rise. It is noted that the highest radiation value (approximately 860 W/m$^2$) occurs at a temperature of approximately 24°C, where the engine speed reaches its highest value (1317 rpm). Beyond this point, as the temperature continues to increase to 25.8°C, both radiation intensity and engine speed decline, indicating an optimal temperature threshold for optimizing system efficiency (or engine performance in this context).

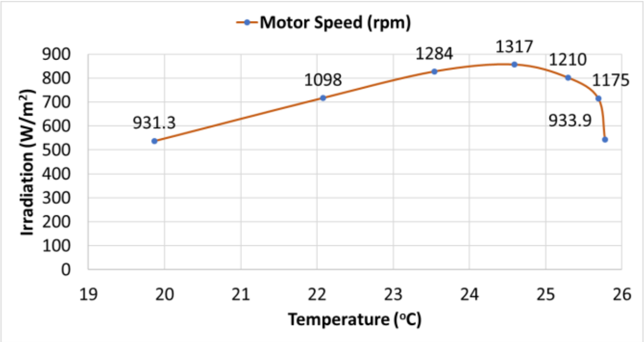


Fig. 20. IM Speed with variable weather conditions in PV system

From this figure, it can be concluded that optimal engine performance, in terms of rotational speed, is linked to a certain level of solar radiation, which in turn is affected by temperature. Beyond this level, environmental conditions begin to negatively impact performance, which may indicate a need for cooling or improved thermal management to maintain high performance.

Fig. 21 shows the relationship between temperature (°C) and system efficiency, with irradiance (W/m²) as the influencing environmental component. The curve shows that efficiency gradually increases with increasing solar irradiance and temperature until it reaches its highest value (48.4%) at approximately 860 W/m² solar irradiance, 24°C. Beyond this point, efficiency begins to decline significantly despite the continued increase in temperature, due to thermal losses. In crystalline silicon panels, power decreases by 0.4-0.5% for every degree Celsius above 25°C. Consequently, this indicates that there is a thermal threshold beyond which efficiency begins to decline due to negative thermal effects such as heat loss or reduced conversion efficiency in the system.

Scientifically, this behavior is consistent with the principles of thermal physics, which indicate that most photovoltaic or thermodynamic systems have an optimal temperature range within which they operate at their highest efficiency. Beyond this range, excess heat begins to cause system losses such as increased resistance or thermal stress on components. Thus, the figure provides clear evidence that performance efficiency is not only related to increasing temperature but is also affected by the system's ability to adapt to that increase or dissipate the excess heat.

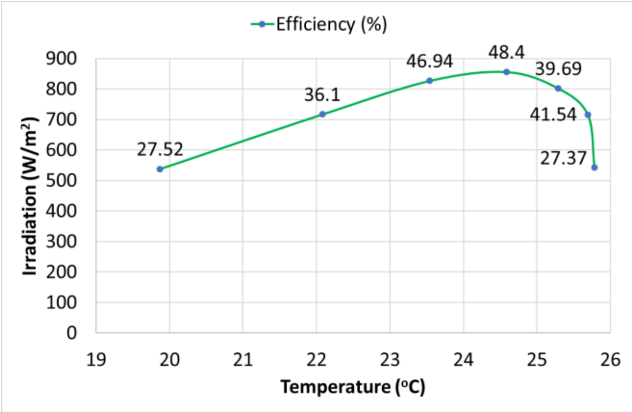


Fig. 21. PV water Pump system efficiency with variable weather conditions

Induction motors are also affected by this, as higher ambient temperatures and winding temperatures increase the resistance of the motor windings. This leads to higher thermal losses, which reduces motor efficiency.

Fig. 22 shows the relationship between temperature (°C) and the total harmonic distortion (THD) of the rotor current, with solar radiation considered as an associated environmental factor. From the values shown, a significant and sudden increase in the THD value is observed at approximately 23.5°C, reaching 168.74% and then 184.37% at 24°C, before returning to its near-initial value (approximately 45%) at higher temperatures. This sudden and irregular increase is an indication of a disturbance in the electrical system's performance.

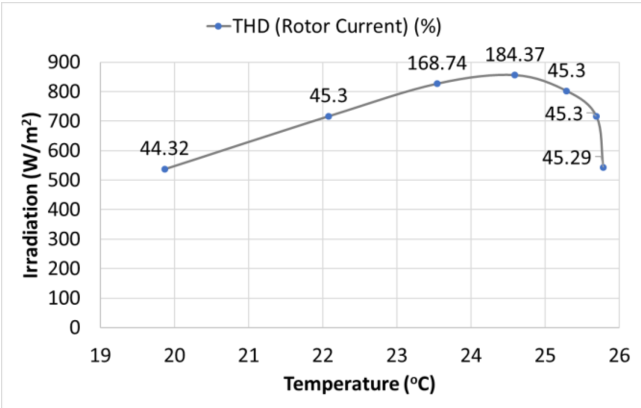


Fig. 22. THD in rotor current of IM with variable weather conditions

High solar radiation increases the inverter switching frequency and power fluctuations, thus leading to higher THD. Similarly, radiation fluctuations (clouds, tracking mismatch) lead to dynamic instability, which increases the THD value. And with PV temperature rising rapidly, reducing voltage is reduced. This causes the inverter to operate near its minimum voltage limit, leading to Poor waveform generation. Unstable operation near PWM limits. High switching noise and voltage harmonics are causing high THD.

A significant increase in THD indicates that the current contains unwanted frequency components that negatively affect the system's efficiency and lifespan and may lead to overheating, unwanted vibrations, or even equipment failure.

Here, should highlight the potential impact of external disturbances, such as dust accumulation, partial shading, and atmospheric fluctuations, on the realistic performance of photovoltaic systems. This is a necessary step to enhance the credibility of the study and link its findings to practical applications. However, these factors were not included in the current modeling due to the research's focus on analyzing theoretical performance or under certain ideal conditions, allowing for the isolation of the influence of the main variables under study. This approach is common in preliminary or analytical studies, where it is preferable to simplify the model to understand the behavior of the underlying system before incorporating environmental complexities. This also opens up future prospects for later model expansion to include the influence of these factors within a more comprehensive simulation framework.

## IV. Conclusions

A solar photovoltaic water pumping system (SPVWPS) was designed, taking into account water requirements, solar radiation resources, and the optimal tilt angle and orientation of the panels. The MATLAB/Simulink simulation environment was used to analyze the performance of the designed system. This paper focuses on the analysis of an irrigation system consisting of a 22 kW three-phase induction motor connected to a solar photovoltaic system under the climatic operating conditions of Mosul, Iraq. The results showed that operating the water pump using the solar system led to a decrease in the motor torque by 9% and the motor efficiency decreased by 34.3% compared to when supplied with electrical power from the grid. Also, The results shown that the system's best performance is achieved at 24°C, with a motor speed of 1,317 rpm, peak efficiency of 48.4%, and an irradiance of approximately 860 W/m². Prior to this point, the values gradually increased with increasing temperature; for example, at 22°C, the speed was 1,098 rpm and the efficiency were 36.1%. After 24°C, the values began to decline: at 25.3°C, the speed dropped to 933.9 rpm and the efficiency to 27.37%. As for the harmonic distortion (THD) in the rotor current, it spiked sharply at 23.5°C, reaching a THD of 168.74%. It then peaked at 24°C at 184.37% before returning to normal (approximately 45.3%) at higher temperatures. The importance of this study is to provide a more reproducible and in-depth interpretation of the simulation results, which represents a valuable study for both technical personnel and engineers working in the field of photovoltaic integration, as well as for machinery engineers.

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## References

[1] F. Raza *et al*., "The Socio-Economic Impact of Using Photovoltaic (PV) Energy for High-Efficiency Irrigation Systems: A Case Study," *Energies*, vol. 15, no. 3, p. 1198, Feb. 2022, doi: 10.3390/en15031198.

[2] M. Calero-Lara, R. López-Luque, and F. J. Casares, "Methodological Advances in the Design of Photovoltaic Irrigation," *Agronomy*, vol. 11, no. 11, p. 2313, Nov. 2021, doi: 10.3390/agronomy11112313.

[3] F. B. Ismail, M. A. A. Rahmat, H. A. Kazem, A. S. M. Al-Obaidi, and M. S. Ridwan, "Maximizing energy via solar-powered smart irrigation: An approach utilizing a single-axis solar tracking mechanism," *Irrig. Drain*., vol. 73, no. 3, pp. 829–845, Jul. 2024, doi: 10.1002/ird.2937.

[4] S. A. S. Yahiaoui Maamar, I. M. Elzein, A. Benameur, H. Mohamed, M. M. Mahmoud, and M. I. Mosaad, "A Comparative Analysis of Recent MPPT Algorithms (P&O\INC\FLC) for PV Systems," *J. Robot. Control*, vol. 6, no. 4, pp. 1581–1588, 2025, doi: 10.18196/jrc.v6i4.25814 1581.

[5] A. K. Mishra and B. Singh, "Solar-powered switched reluctance motor-driven water pumping system with battery support," *IET Power Electron*., vol. 14, no. 5, pp. 1018–1031, Apr. 2021, doi: 10.1049/pel2.12084.

[6] J. I. Herraiz, J. Fernández-Ramos, R. Hogan Almeida, E. M. Báguena, M. Castillo-Cagigal, and L. Narvarte, "On the tuning and performance of Stand-Alone Large-Power PV irrigation systems," *Energy Convers. Manag. X*, vol. 13, p. 100175, Jan. 2022, doi: 10.1016/j.ecmx.2021.100175.

[7] O. V. Shepovalov, A. T. Belenov, and S. V. Chirkov, "Review of photovoltaic water pumping system research," *Energy Reports*, vol. 6. pp. 306–324, 2020, doi: 10.1016/j.egyr.2020.08.053.

[8] A. Gündoğdu and B. Güre, "Design, Construction and Implementation of Low Cost Photovoltaic Water Pumping System for Agricultural Irrigatin," *Balk. J. Electr. Comput. Eng.*, vol. 7, no. 1, pp. 72–80, 2019, doi: 10.17694/bajece.492804.

[9] W. Hassan and F. Kamran, "A hybrid PV/utility powered irrigation water pumping system for rural agricultural areas," *Cogent Eng*., vol. 5, no. 1, p. 1466383, Jan. 2018, doi: 10.1080/23311916.2018.1466383.

[10] V. Kumar Yadav, R. Yadav, R. Singh, I. Mishra, I. Ganvir, and Manish, "Reconfiguration of PV array through recursive addition approach for optimal power extraction under PSC," *Energy Convers. Manag*., vol. 292, p. 117412, Sep. 2023, doi: 10.1016/j.enconman.2023.117412.

[11] A. A. S. Sunil Rao, G. Muniraju, C. Tepedelenlioglu, D. Srinivasan, and G. Tamizhmani, "Dropout and Pruned Neural Networks for Fault Classification in Photovoltaic Arrays," *IEEE Access*, vol. 9, pp. 120034–120042, 2021.

[12] S. S. Chandel, M. N. Naik, and R. Chandel, "Review of performance studies of direct coupled photovoltaic water pumping systems and case study," *Renew. Sustain. Energy Rev*., vol. 76, pp. 163–175, Sep. 2017, doi: 10.1016/j.rser.2017.03.019.

[13] A. Mokeddem, A. Midoun, D. Kadri, S. Hiadsi, and I. A. Raja, "Performance of a directly-coupled PV water pumping system," *Energy Convers. Manag*., vol. 52, no. 10, pp. 3089–3095, Sep. 2011, doi: 10.1016/j.enconman.2011.04.024.

[14] S. S. Chandel, M. Nagaraju Naik, and R. Chandel, "Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies," *Renew. Sustain. Energy Rev*., vol. 49, pp. 1084–1099, Sep. 2015, doi: 10.1016/j.rser.2015.04.083.

[15] L. Gevorkov, J. L. Domínguez-García, and L. T. Romero, "Review on Solar Photovoltaic-Powered Pumping Systems," *Energies*, vol. 16, no. 1, p. 94, Dec. 2022, doi: 10.3390/en16010094.

[16] G. Li, Y. Jin, M. W. Akram, and X. Chen, "Research and current status of the solar photovoltaic water pumping system – A review," *Renew. Sustain. Energy Rev*., vol. 79, pp. 440–458, Nov. 2017, doi: 10.1016/j.rser.2017.05.055.

[17] L. A. Kumar, C. N. Lakshmiprasad, G. Ramaraj, and G. Sivasurya, "Design, simulation of different configurations and life-cycle cost analysis of solar photovoltaic–water-pumping system for agriculture applications: use cases and implementation issues," *Clean Energy*, vol. 6, no. 2, pp. 335–352, Apr. 2022, doi: 10.1093/ce/zkac018.

[18] V. S. Korpale, D. H. Kokate, and S. P. Deshmukh, "Performance Assessment of Solar Agricultural Water Pumping System," *Energy Procedia*, vol. 90, pp. 518–524, Dec. 2016, doi: 10.1016/j.egypro.2016.11.219.

[19] F. Belgacem, M. Mostefai, M. Yahia, and A. Belgacem, "Optimization of Photovoltaic Water Pumping System Based on BLDC Motor for Agricultural Irrigation with Different MPPT Methods," *Period. Polytech. Electr. Eng. Comput. Sci*., vol. 66, no. 4, pp. 315–324, Oct. 2022, doi: 10.3311/PPee.20140.

[20] R. A. Othman and O. S. A. D. Yehya Al-Yozbaky, "Influence of reactive power compensation from PV systems on electrical grid," *Int. J. Power Electron. Drive Syst*., vol. 14, no. 2, pp. 1172–1183, 2023, doi: 10.11591/ijpeds.v14.i2.pp1172-1183.

[21] P. Choudhary, R. K. Srivatava, and S. De, "Solar powered induction motor based water pumping system: A review of components, parameters and control methodologies," in *2017 4th IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics, UPCON 2017*, pp. 666–674, 2017, doi: 10.1109/UPCON.2017.8251129.

[22] A.-R. Bawa, A. K. Sunnu, and E. A. Sarsah, "Recent Advances in Solar-powered Photovoltaic Pumping Systems for Drip Irrigation," *iRASD J. Energy Environ.*, vol. 4, no. 2, pp. 112–132, Dec. 2023, doi: 10.52131/jee.2023.0402.0040.

[23] U. Sharma and B. Singh, "Utility-Tied Solar Water Pumping System for Domestic and Agricultural Applications," *J. Inst. Eng. Ser. B*, vol. 101, no. 1, pp. 79–91, Feb. 2020, doi: 10.1007/s40031-020-00426-z.

[24] M. A. Gebul, "Trend, Status, and Challenges of Irrigation Development in Ethiopia—A Review," *Sustainability*, vol. 13, no. 10, p. 5646, May 2021, doi: 10.3390/su13105646.

[25] R. A. Othman and O. S. A.-D. Al-Yozbaky, "Effect of Reactive Power Capability of the PV Inverter on the Power System Quality," *Indones. J. Electr. Eng. Informatics*, vol. 10, no. 4, pp. 780–795, Dec. 2022, doi: 10.52549/ijeei.v10i4.3913.

[26] R. Chinthamalla, R. Karampuri, S. Jain, P. Sanjeevikumar, and F. Blaabjerg, "Dual Solar Photovoltaic Fed Three-Phase Open-End Winding Induction Motor Drive for Water Pumping System Application," *Electr. Power Components Syst*., vol. 46, no. 16–17, pp. 1896–1911, Oct. 2018, doi: 10.1080/15325008.2018.1520324.

[27] J. Reca-Cardeña and R. López-Luque, "Design Principles of Photovoltaic Irrigation Systems," in *Advances in Renewable Energies and Power Technologies*, pp. 295–333, 2018, doi: 10.1016/B978-0-12-812959-3.00009-5.

[28] S. V. Rami Reddy *et al*., "TS fuzzy control of PV assisted single phase three phase induction motor drive for rural pumping applications," *Trans. Energy Syst. Eng. Appl*., vol. 5, no. 1, pp. 1–17, Apr. 2024, doi: 10.32397/tesea.vol5.n1.537.

[29] A. T. Mohsin and I. M. Abdulbaqi, "Analysis of an Irrigation Pump Driver Fed by Solar PV Panels (Part II)," in *2018 International Conference on Engineering Technology and their Applications (IICETA)*, pp. 1–6, 2018, doi: 10.1109/IICETA.2018.8458080.

[30] M. J. Mohana Rao, M. Kumar Sahu, and P. Kumar Subudhi, "Pv based water pumping system for agricultural sector," *Mater. Today Proc*., vol. 5, no. 1, pp. 1008–1016, 2018, doi: 10.1016/j.matpr.2017.11.177.

[31] D. Bojang, E. Nhantumbo, M. Verma, and A. Kulkarni, "PV-Fed Single-Phase Induction Motor for Irrigation Application," *J. Inst. Eng. Ser. B*, vol. 105, no. 2, pp. 335–342, Apr. 2024, doi: 10.1007/s40031-023-00975-z.

[32] S. Kalasathya, "Implementation of Solar Power Ac Motor Pump Set on MPPT With Battery Backup For Agriculture System," *Int. J. Eng. Comput. Sci*., vol. 2, pp. 18928–18933, Nov. 2016, doi: 10.18535/ijecs/v5i11.36.

[33] K. Kenge, M. Hasija, R. Tare, and S. S. Raghuwanshi, "Mathematical Modelling and Implementation of Solar Based Water Pumping System for Irrigation," *Int. J. Recent Technol. Eng*., vol. 8, no. 5, pp. 5596–5601, Jan. 2020, doi: 10.35940/ijrte.E6706.018520.

[34] L. R. Valer, T. A. Melendez, M. C. Fedrizzi, R. Zilles, and A. M. de Moraes, "Variable-speed drives in photovoltaic pumping systems for irrigation in Brazil," *Sustainable Energy Technologies and Assessments*, vol. 15. pp. 20–26, 2016, doi: 10.1016/j.seta.2016.03.003.

[35] J. Reca, C. Torrente, R. López-Luque, and J. Martínez, "Feasibility analysis of a standalone direct pumping photovoltaic system for irrigation in Mediterranean greenhouses," *Renew. Energy*, vol. 85, pp. 1143–1154, Jan. 2016, doi: 10.1016/j.renene.2015.07.056.

[36] B. Bouzidi, "New sizing method of PV water pumping systems," *Sustain. Energy Technol. Assessments*, vol. 4, pp. 1–10, 2013, doi: 10.1016/j.seta.2013.08.004.

[37] V. H. Kumar, R. Patel, L. K. Sahu, and Y. Kishor, "Solar photovoltaic-integrated energy storage system with a power electronic interface for operating a brushless DC drive-coupled agricultural load," *Energy Harvest. Syst*., vol. 11, no. 1, Apr. 2024, doi: 10.1515/EHS-2023-0127.

[38] S. F. A. Bukhari, H. Kahveci, and M. E. Şahin, "Single Phase Induction Motor Driver for Water Pumping Powered by Photovoltaic System," *Electronics*, vol. 14, no. 6, p. 1189, Mar. 2025, doi: 10.3390/electronics14061189.

[39] Z. K. Gurgi, A. I. Abdalla, and E. D. Hassan, "Simulation analysis of DC motor based solar water pumping system for agriculture applications in Rural areas," *Int. J. Power Electron. Drive Syst*., vol. 14, no. 4, p. 2409, Dec. 2023, doi: 10.11591/ijpeds.v14.i4.pp2409-2417.

[40] S. BalaKumar, M. Lemma, and M. Godato, "Solar-powered ANN-based MPPT with zeta converter for BLDC motor water pumping in rural Ethiopia for sustainable agriculture," *Discov. Sustain*., vol. 6, no. 1, p. 140, Feb. 2025, doi: 10.1007/s43621-025-00893-8.

[41] V. Kavya, V. Jegathesan, and T. Jarin, "A novel approach for solar combined open-ended winding induction machine for agriculture water pumping applications," *Meas. Sensors*, vol. 33, p. 101141, Jun. 2024, doi: 10.1016/j.measen.2024.101141.

[42] E. Nhantumbo, D. Bojang, M. Verma, and A. Kulkarni, "Design of a PV-Fed Drive System with a Single-Phase Induction Motor for Irrigation Application," *E3S Web Conf*., vol. 405, p. 02026, Jul. 2023, doi: 10.1051/e3sconf/202340502026.

[43] H. Attia, M. Takruri, and A. Al-Ataby, "Intelligent algorithm-based maximum power point tracker for an off-grid photovoltaic-powered direct-current irrigation system," *Clean Energy*, vol. 8, no. 3, pp. 48–61, Jun. 2024, doi: 10.1093/ce/zkae023.

[44] N. S. Okomba, A. O. Esan, B. A. Omodunbi, A. A. Sobowale, O. O. Adanigbo, and O. O. Oguntuase, "Iot Based Solar Powered Pump For Agricultural Irrigation And Control System," *Fudma J. Sci*., vol. 7, no. 6, pp. 192–199, Dec. 2023, doi: 10.33003/fjs-2023-0706-2056.

[45] S. R. Gundala *et al*., "Enhancing the solar water pumping efficiency through Beta MPPT method-controlled drive," *Trans. Energy Syst. Eng. Appl*., vol. 5, no. 1, pp. 1–13, May 2024, doi: 10.32397/tesea.vol5.n1.568.

[46] A. Yahia, M. T. Makhloufi, K. Chafaa, N. Terki, and M. Hamiane, "Enhanced Maximum Power Point Tracking for Photovoltaic Systems Using Adaptive Fuzzy Control," *J. Robot. Control*, vol. 6, no. 3, pp. 1434–1449, 2025, doi: 10.18196/jrc.v6i3.26451.

[47] S. G. Malla, P. Malla, M. Karthik, D. S. Kumar, and H. Awad, "Modified Invasive Weed Optimization for the Control of Photovoltaic Powered Induction Motor Drives in Water Pumping Systems," *Iran. J. Sci. Technol. Trans. Electr. Eng*., vol. 47, no. 3, pp. 925–938, Sep. 2023, doi: 10.1007/s40998-023-00589-7.

[48] N. El Ouanjli *et al*., "Modern improvement techniques of direct torque control for induction motor drives - a review," *Prot. Control Mod. Power Syst*., vol. 4, no. 2, pp. 1–12, Apr. 2019, doi: 10.1186/s41601-019-0125-5.

[49] D. Balamurali *et al*., "A solar-powered, internet of things (IoT)-controlled water irrigation system supported by rainfall forecasts utilizing aerosols: a review," *Environ. Dev. Sustain*., Jan. 2025, doi: 10.1007/s10668-024-05953-z.

[50] T. A. Manfo and M. E. Şahin, "Development of an Automatic Photovoltaic Cell-Battery Powered Water Irrigation System Incorporated with Arduino Software for Agricultural Activities," *Gazi J. Eng. Sci*., vol. 10, no. 2, pp. 314–328, Aug. 2024, doi: 10.30855/gmbd.0705A07.

[51] A. Morchid, R. Jebabra, H. M. Khalid, R. El Alami, H. Qjidaa, and M. Ouazzani Jamil, "IoT-based smart irrigation management system to enhance agricultural water security using embedded systems, telemetry data, and cloud computing," *Results Eng*., vol. 23, p. 102829, Sep. 2024, doi: 10.1016/j.rineng.2024.102829.

[52] S. J. Sarkar, P. K. Kundu, S. K. Sahoo, T. K. Panigrahi, P. S. Patro, and A. Rajak, "Development of utility assisting controllers for solarised irrigation system," *Renew. Energy Focus*, vol. 45, pp. 53–67, Jun. 2023, doi: 10.1016/j.ref.2023.02.004.

[53] R. A. Othman and O. S. Alyozbaky, "A Novel Method to Improve the Power Quality Via Hybrid System," *Prz. Elektrotechniczny*, vol. 2023, no. 6, pp. 167–174, Jun. 2023, doi: 10.15199/48.2023.06.35.

[54] M. A. Qasim and T. H. Atyia, "Design and implementation of VSI for solar water pump control," *Tikrit J. Eng. Sci*., vol. 31, no. 1, pp. 193–210, 2024.

[55] S. J. Sarkar, P. K. Kundu, S. K. Sahoo, D. Dehury, S. Patri, and F. Yanine, "Development of a low cost, microcontroller less irrigation pump controller for solarised irrigation system," in *2021 Innovations*

*in Power and Advanced Computing Technologies (i-PACT)*, pp. 1–6, 2021.

[56] J. Cho, S. M. Park, A. Reum Park, O. C. Lee, G. Nam, and I. H. Ra, "Application of photovoltaic systems for agriculture: A study on the relationship between power generation and farming for the improvement of photovoltaic applications in agriculture," *Energies*, vol. 13, no. 18. pp. 1–18, 2020. doi: 10.3390/en13184815.

[57] A. Loubna, T. Riad, and M. Salima, "Standalone photovoltaic array fed induction motor driven water pumping system," *Int. J. Electr. Comput. Eng.*, vol. 10, no. 5, p. 4534, Oct. 2020, doi: 10.11591/ijece.v10i5.pp4534-4542.

[58] A. Harkani and A. El Aissaoui, "Performance study of a standalone direct pumping photovoltaic system used for drip irrigation," *Agricultural Engineering International: CIGR Journal*, vol. 21, no. 3, pp. 114-122, 2019.

[59] S. S. Dessouky, A. A. Elbaset, A. H. K. Alaboudy, H. A. Ibrahim, and S. A. M. Abdelwahab, "Performance improvement of a PV-powered induction-motor-driven water pumping system," *2016 18th International Middle-East Power Systems Conference, MEPCON 2016 - Proceedings*., pp. 373–379, 2017, doi: 10.1109/MEPCON.2016.7836918.

[60] J. Kapica, "Small scale stand-alone photovoltaic pumping system with brushless DC motor for irrigation in agriculture," *J. Renew. Sustain. Energy*, vol. 9, no. 6, pp. 1–14, 2017, doi: 10.1063/1.4991456.

[61] B. Singh, U. Sharma, and S. Kumar, "Standalone Photovoltaic Water Pumping System Using Induction Motor Drive With Reduced Sensors," *IEEE Trans. Ind. Appl*., vol. 54, no. 4, pp. 3645–3655, Jul. 2018, doi: 10.1109/TIA.2018.2825285.

[62] A. Khiareddine, C. Ben Salah, and M. F. Mimouni, "Power management of a photovoltaic/battery pumping system in agricultural experiment station," *Sol. Energy*, vol. 112, pp. 319–338, Feb. 2015, doi: 10.1016/j.solener.2014.11.020.

[63] S. Pant and R. P. Saini, "Solar Water Pumping System Modelling and Analysis using MATLAB/Simulink," in *2020 IEEE Students Conference on Engineering & Systems (SCES)*, pp. 1–6, 2020, doi: 10.1109/SCES50439.2020.9236716.

[64] K. A. Sado, L. H. Hassan, and M. Moghavvemi, "Design of a PV-powered DC water pump system for irrigation: a case study," in *2018 53rd International Universities Power Engineering Conference (UPEC)*, pp. 1–6, 2018, doi: 10.1109/UPEC.2018.8542072.

[65] S. Biswas and M. T. Iqbal, "Dynamic Modelling of a Solar Water Pumping System with Energy Storage," *J. Sol. Energy*, vol. 2018, no. 1, pp. 1–12, Apr. 2018, doi: 10.1155/2018/8471715.

[66] M. V. Hadole, P. Bajpai, and K. N. Tiwari, "Modeling and planning operation of directly coupled solar photovoltaic pump operated drip irrigation system with a case study," *Clean Technol. Environ. Policy*, vol. 24, no. 9, pp. 2911–2929, Nov. 2022, doi: 10.1007/s10098-022-02376-0.

[67] Kunaifi, Liliana, H. Simaremare, Mulyono, and W. Anjarjati, "Design and Analysis of Solar Water Pumping for Salt Production in Indonesia," *IOP Conf. Ser. Earth Environ. Sci*., vol. 927, no. 1, p. 012021, Dec. 2021, doi: 10.1088/1755-1315/927/1/012021.

[68] D. A. Pham, "Modeling and Simulation of Photovoltaic Pumping System Used for Irrigation," in *2021 9th International Renewable and Sustainable Energy Conference (IRSEC)*, pp. 1–5, 2021, doi: 10.1109/IRSEC53969.2021.9740735.

[69] S. K. Kakodia and G. Dyanamina, "Matlab/Simulation of Solar PV Array Powered Speed Control of IM Drive for Water Pumping," in *2021 International Conference on Control, Automation, Power and Signal Processing (CAPS)*, pp. 1–5, 2021, doi: 10.1109/CAPS52117.2021.9730676.

[70] P. Jain and D. K. Palwalia, "SPV Water Pumping system using Induction Motor Drive For Stand-Alone Application With Minimum Sensors," in *2019 Global Conference for Advancement in Technology (GCAT)*, pp. 1–4, 2019, doi: 10.1109/GCAT47503.2019.8978420.

[71] R. Kumari and R. Dahiya, "Speed control of solar water pumping with indirect vector control technique," in *2018 2nd International Conference on Inventive Systems and Control (ICISC)*, pp. 1401–1406, 2018, doi: 10.1109/ICISC.2018.8399039.

[72] R. K. Singh, A. Kumar, and B. K. Naick, "Optimised Solar Power Fed Induction Motor Drive for Water Pumping Application Along with Load," in *2018 International Electrical Engineering Congress (iEECON)*, pp. 1–4, 2018, doi: 10.1109/IEECON.2018.8712192.

[73] U. K. Kalla, N. Bhati, K. Chariya, and I. Qureshi, "Design and Analysis of Solar PV Fed IMD Water - Pumping System," in *2021 International Conference on Sustainable Energy and Future Electric Transportation (SEFET)*, pp. 1–6, 2021, doi: 10.1109/SeFet48154.2021.9375744.

[74] M. Sarvi and A. Azadian, "A comprehensive review and classified comparison of MPPT algorithms in PV systems," *Energy Syst.*, vol. 13, no. 2, pp. 281–320, May 2022, doi: 10.1007/s12667-021-00427-x.

[75] R. Jenitha and K. Rajesh, "Radial basis function neural network MPPT controller-based microgrid for hybrid stand-alone energy system used for irrigation," *Circuit World*, vol. 49, no. 2, pp. 251–266, Apr. 2023, doi: 10.1108/CW-03-2022-0076.

[76] R. B. A. Koad, A. F. Zobaa, and A. El-Shahat, "A Novel MPPT Algorithm Based on Particle Swarm Optimization for Photovoltaic Systems," *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 468–476, Apr. 2017, doi: 10.1109/TSTE.2016.2606421.

[77] R. Veramalla, R. Voddamalla, S. R. Salkuti, and V. Nagamalleswari, "MPPT Algorithms for Solar PV–Drip Irrigation System," in *Power Quality in Microgrids: Issues, Challenges and Mitigation Techniques*, pp. 275–299, 2023, doi: 10.1007/978-981-99-2066-2_13.

[78] M. A. E. Salama, N. M. El-Naggar, and S. Abu-Zaid, "Energy saving analysis for pump-motor set in water purification plant using variable speed drive," *Sci. Rep*., vol. 14, no. 1, p. 27728, 2024, doi: 10.1038/s41598-024-75601-z.

[79] M. Errouha, S. Motahhir, Q. Combe, and A. Derouich, "Intelligent control of induction motor for photovoltaic water pumping system," *SN Appl. Sci*., vol. 3, no. 9, 2021, doi: 10.1007/s42452-021-04757-4.

[80] A. Belgacem, Y. Miloud, M. Mostefai, and F. Belgacem, "Fuzzy logic direct torque control of induction motor for photovoltaic water pumping system," *Int. J. Power Electron. Drive Syst*., vol. 13, no. 3, pp. 1822–1832, 2022, doi: 10.11591/ijpeds.v13.i3.pp1822-1832.