

Performance Evaluation of Indirect Rotor Field-Oriented Control for Dual Stator Induction Motor in Photovoltaic Water Pumping Systems

SAHNOUN M'hamed^{1*}, SADOUNI Radhwane¹, DJERIOU Salim²

¹Material, Energy Systems Technology and Environment Laboratory, Faculty of Sciences and Technologie, University of Ghardaia, Algeria

²Department of Electrical Engineering, University M'Sila
M'Sila, Algeria

*Corresponding author; Email: sahnoun.mhamed@univ-ghardaia.edu.dz

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ABSTRACT

The growing need for efficient irrigation in remote regions has accelerated interest in photovoltaic water pumping systems (PVWPS) as a sustainable alternative to diesel-powered solutions. This study focuses on enhancing the performance of a standalone solar pumping system by implementing an indirect rotor field-oriented control (IRFOC) approach for a dual-stator induction motor (DSIM). The control framework is divided into two stages: first, a Perturb and Observe (P&O) algorithm maximizes energy extraction from the photovoltaic generator (PVG) via a DC-DC boost converter; second, motor speed is regulated using IRFOC, with a dynamic reference derived from a speed optimization mechanism responsive to solar irradiance variations. Two IRFOC strategies are evaluated, one using conventional PI controllers for both speed and current regulation, and another relying on model-based current estimation to reduce system complexity. Simulations under variable solar conditions validate the effectiveness of the proposed configurations, highlighting trade-offs in torque ripple, speed tracking accuracy, and control robustness.

I. Introduction

The global shift toward sustainable energy has intensified the adoption of photovoltaic (PV) technology in off-grid applications, particularly in water pumping systems designed for rural and agricultural zones. These standalone photovoltaic water pumping systems (PVWPS) present a cost-effective and environmentally responsible solution in areas where grid connectivity is limited or impractical [1], [2]. However, one of the primary challenges facing PVWPS is their sensitivity to fluctuating solar irradiance, which directly impacts the power output of the photovoltaic generator (PVG) and introduces instability into the system's operation [3].

To maintain optimal efficiency, the motor-pump unit must be operated at a speed that adapts dynamically to the available PV power. For this reason, the integration of intelligent motor control strategies has gained attention. Among these, indirect rotor field-oriented control (IRFOC) has emerged as a reliable solution for induction motor control, offering decoupled regulation of torque and flux, improved dynamic performance, and high operational efficiency [4], [5].

Multi-phase machines, such as the dual stator induction motor (DSIM), have demonstrated considerable advantages over conventional three-phase motors in PV pumping applications, including enhanced fault tolerance, reduced torque ripple, and improved thermal performance [3]. Recent studies have explored various

implementations of IRFOC in DSIM-based systems. For example, a fuzzy controller applied to IRFOC was shown to improve torque control under variable conditions [5], while other works highlighted the benefits of replacing current sensors with model-based observers to reduce hardware complexity [9], [10].

In the context of MPPT (Maximum Power Point Tracking), the Perturb and Observe (P&O) algorithm remains a commonly used technique due to its simplicity and practical implementation [6]. However, its effectiveness depends heavily on the robustness of the downstream motor control and the ability to adjust the operating point dynamically.

Previous works, such as in [4] and [5], utilized multiple PI controllers for current and speed regulation in IRFOC to maintain accurate motor control. However, this structure increases computational burden and sensitivity to parameter variation. Alternatively, a sensorless approach based on mathematical modeling has been proposed in [10], which eliminates the need for current feedback and simplifies the controller design.

II. Design of Photovoltaic Water Pumping System

The proposed photovoltaic water pumping system (PVWPS) is structured as a two-stage configuration that integrates both power conditioning and motor control to optimize performance under changing irradiance conditions. As illustrated in Figure 1, the system is composed of a photovoltaic generator (PVG), a DC-DC boost converter regulated via an MPPT algorithm, and a dual stator induction motor (DSIM) driven by two voltage source inverters (VSI) under an indirect rotor field-oriented control (IRFOC) strategy. The reference speed for the motor is dynamically adjusted using a speed optimization method, ensuring optimal operation across varying solar conditions [4].

II.1. Modelling of the photovoltaic generator

The PV generator is modeled based on the widely used single-diode equivalent circuit Figure 2, which includes a current source representing the photocurrent I_{ph} , a diode d , a series resistance R_s , and a shunt resistance R_{sh} . The output current of the panel I_{pv} can be expressed using the following equation:

$$I_{pv} = I_{ph} - I_d - I_{sh} = I_{ph} - I \left(e^{\left(\frac{q(V_{pv} + R_s I)}{KAT} \right)} - 1 \right) - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (1)$$

This model accounts for the nonlinear behavior of the PV module under varying temperature and irradiance levels, enabling accurate power estimation. A DC-DC boost converter is used to raise the output voltage of the PVG to match the motor's voltage requirements. The converter's duty cycle a is continuously adjusted by the MPPT algorithm to ensure operation at the maximum power point.

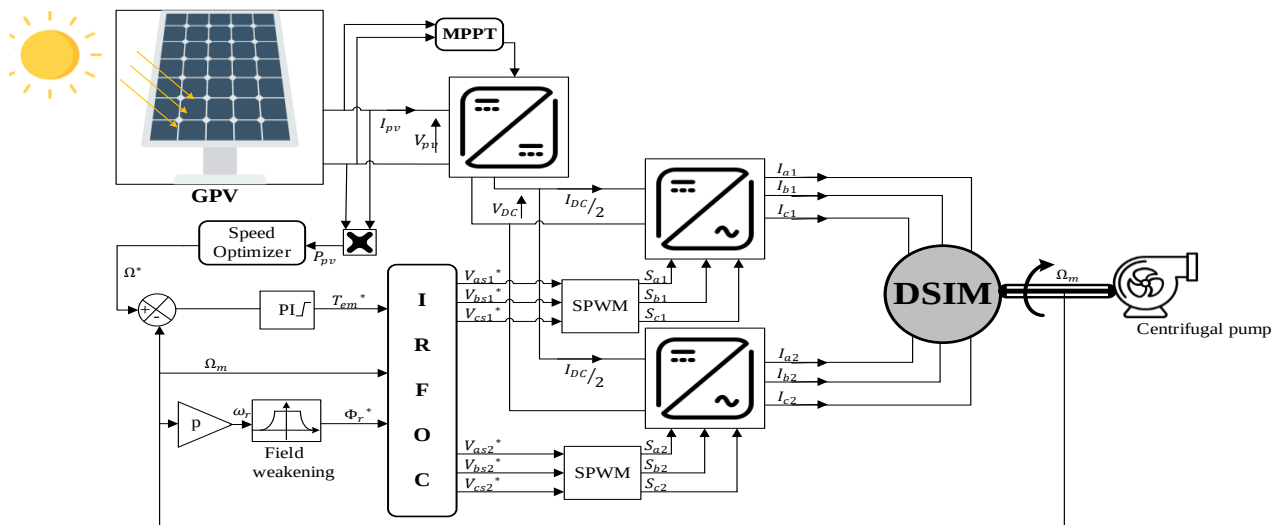


Figure 1 System configuration of the proposed PVWPS

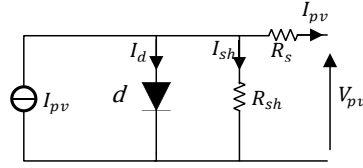


Figure 2PV module equivalent circuit [4]

II.2. Modelling of the motor-pump

The centrifugal pump is mechanically coupled to the DSIM and exhibits a quadratic torque-speed relationship, as typical in such systems:[5]

$$T_{pump} = A_p \Omega_m^2 \quad (2)$$

Where A_p It Is a constant derived from the nominal conditions:

$$A_p = P_n / \Omega_m^3 \quad (3)$$

Here, P_n is the rated power, and Ω_n It is the nominal angular speed of the motor.

To reduce modeling complexity, the DSIM is represented in synchronous. dq -Reference frame using Park transformation. This leads to the following voltage and flux equations for the two stator windings and the rotor:

- Stator Voltage Equations:

$$\begin{cases} V_{ds1} = R_{s1} + \frac{d\Phi_{ds1}}{dt} - \omega_s \Phi_{qs1} \\ V_{qs1} = R_{s1} + \frac{d\Phi_{qs1}}{dt} + \omega_s \Phi_{ds1} \\ V_{ds2} = R_{s2} + \frac{d\Phi_{ds2}}{dt} - \omega_s \Phi_{qs2} \\ V_{qs2} = R_{s2} + \frac{d\Phi_{qs2}}{dt} + \omega_s \Phi_{ds2} \end{cases} \quad (4)$$

- Rotor Voltage Equations:

$$\begin{cases} 0 = R_r I_{dr} + \frac{d\Phi_{dr}}{dt} - \omega_{sr} \Phi_{qr} \\ 0 = R_r I_{qr} + \frac{d\Phi_{qr}}{dt} + \omega_{sr} \Phi_{dr} \end{cases} \quad (5)$$

- Flux Linkage Equations:

$$\begin{cases} \Phi_{ds1} = L_{s1} I_{ds1} + L_m (I_{ds1} + I_{ds2} + I_{dr}) \\ \Phi_{qs1} = L_{s1} I_{qs1} + L_m (I_{qs1} + I_{qs2} + I_{qr}) \\ \Phi_{ds2} = L_{s2} I_{ds2} + L_m (I_{ds1} + I_{ds2} + I_{dr}) \\ \Phi_{qs2} = L_{s2} I_{qs2} + L_m (I_{qs1} + I_{qs2} + I_{qr}) \\ \Phi_{dr} = L_r I_{dr} + L_m (I_{ds1} + I_{ds2} + I_{dr}) \\ \Phi_{qr} = L_r I_{qr} + L_m (I_{qs1} + I_{qs2} + I_{qr}) \end{cases} \quad (6)$$

The electromagnetic torque expression:

$$T_{em} = p \frac{L_m}{L_r + L_m} [\Phi_{dr} (I_{qs1} + I_{qs2}) - \Phi_{qr} (I_{ds1} + I_{ds2})] \quad (7)$$

This full system model is used in the simulation environment to predict motor dynamics, pump behavior, and evaluate performance under solar perturbations.

III. Control STRATEGY

Efficient performance in standalone PV water pumping systems requires continuous adaptation to solar variability. To achieve both power extraction and stable motor operation, the system incorporates a two-level control scheme: a Maximum Power Point Tracking (MPPT) algorithm to regulate energy harvesting, and an Indirect Rotor Field-

Oriented Control (IRFOC) strategy for motor speed regulation. A real-time speed optimization mechanism generates the appropriate motor reference based on solar conditions.

III.1. Maximum Power Point Tracking (MPPT)

Given that solar irradiance fluctuates throughout the day, maximizing the harvested power from the PV array is essential. This work utilizes the widely adopted Perturb and Observe (P&O) technique for MPPT due to its ease of implementation and computational efficiency [6][7]. The algorithm perturbs the duty cycle of the DC-DC boost converter and observes the resulting power change. If the power increases, the perturbation direction is retained; if not, it is reversed. Repeating this process ensures convergence toward the PV array's optimal operating point with minimal steady-state oscillation. [4], [6].

III.2. Speed optimizer

To ensure the motor operates efficiently under variable solar conditions, a speed reference is calculated using a curve-fitting approach. This method relies on the known cubic relationship between the motor speed and the mechanical power required by a centrifugal pump:

$$P \approx T_L \Omega_m = A_p \Omega_m^3 \quad (8)$$

Assuming ideal power transfer from the PV generator, the optimal motor speed is derived as:

$$\Omega_{m,opt} = \sqrt[3]{\frac{P_{opt}}{A_p}} \quad (9)$$

III.3. Indirect Rotor Field-Oriented Control (IRFOC)

IRFOC aims to simulate the induction motor operation with a separated excitation DC motor by decoupling the torque and the flux control, with the rotor flux provided by the vector flow generated with the d-axis component, while the q-axis current generates the torque [8]. The primary method is used in the paper [4] this method uses feedback of the quadratic and direct current for the PI controllers and to estimating the motor voltage, due the complexity and their dependence on number of regulators, we implementing a simpler method depend only on a mathematical model of the control technique without need the additional regulator or speed feedback [5], [9], [11].

IV. Simulation Results and Discussion

The simulation of the IRFOC for PVWPS with DSIM, based on the sizing and the demand of the system with varying irradiation, the speed reference is adjusted by PVG power, which depends on irradiance variation. These results are compared to the work done on [4] presented in the right of the figures below that use a different configuration of IRFOC, where the difference between them is the additional current controller for each stator.

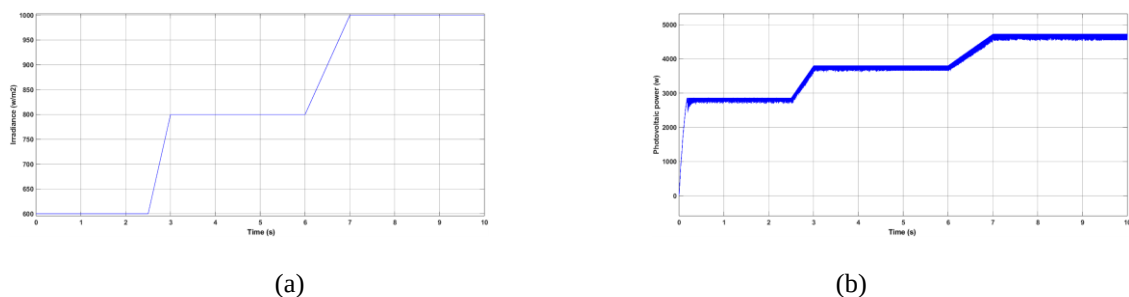


Figure 3. PVG Results,
(a) Irradiance variation, (b) Output PV power

IV.1. Torque and current response

In the Figure 4 a comparison of the electromagnetic torque response of the two methods, highlighting the remarkable deference in the torque ripple, particularly during the steady-state interval, the proposed method Figure 4 (a) demonstrates a significant reduction in torque ripple compared to the alternative configuration Figure 4 (b), which employs the decoupling method without current controllers. This improvement in torque ripple contributes

to smoother operation and enhances system stability. Furthermore, the starting stator current ($I_{s1, start} \approx 20$ A) remains within safe limits using the proposed method, thereby ensuring the motor operates within safe thermal boundaries

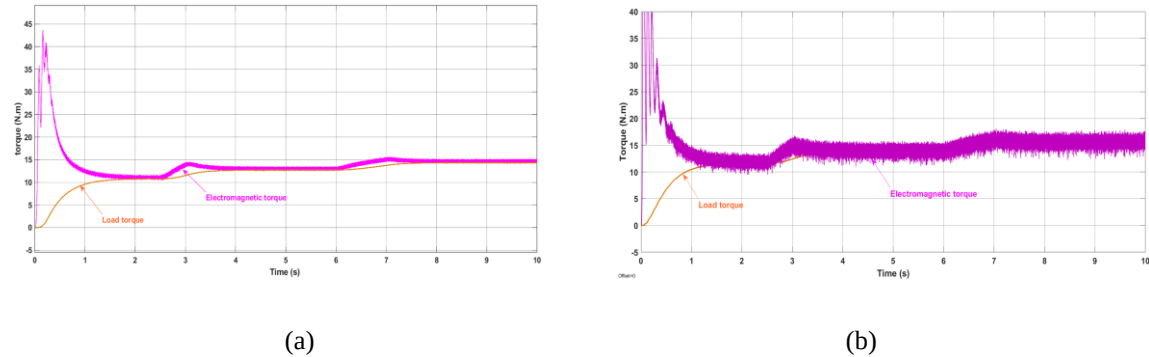


Figure 4. Electromagnetic and load torque,
(a)The proposed method, (b) The alternative configuration

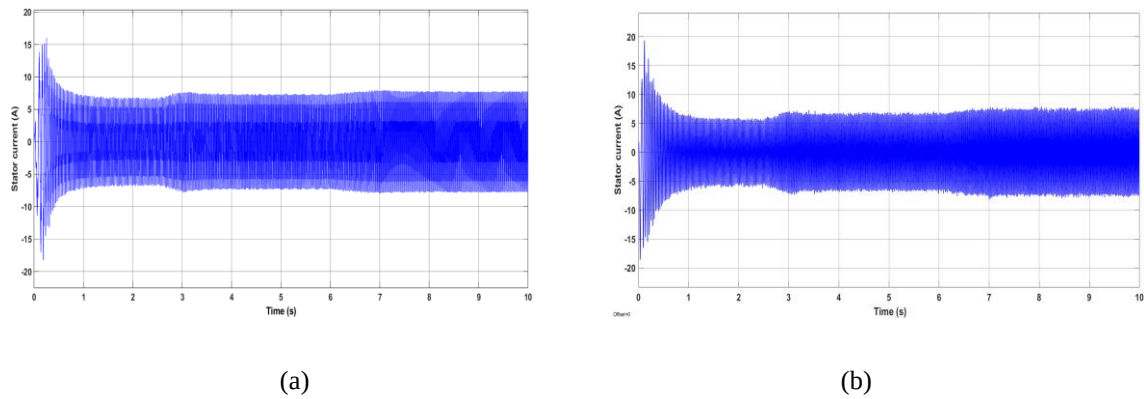


Figure 5. Stator current,
(a)The proposed method, (b) The alternative configuration

IV.2. Speed response

Speed response has resulted in the system tracking the reference that relates to the power PVG under variable irradiance. The result shown in Figure 6 is slightly far from the reference compared to the other configuration, which follows its reference values with good accuracy. As illustrated in the figure, the height and the water flow are proportional to the motor speed. Figure 7 illustrates the power generated from the PVG and output, clarifying that the cause of the error in the speed is the power losses.

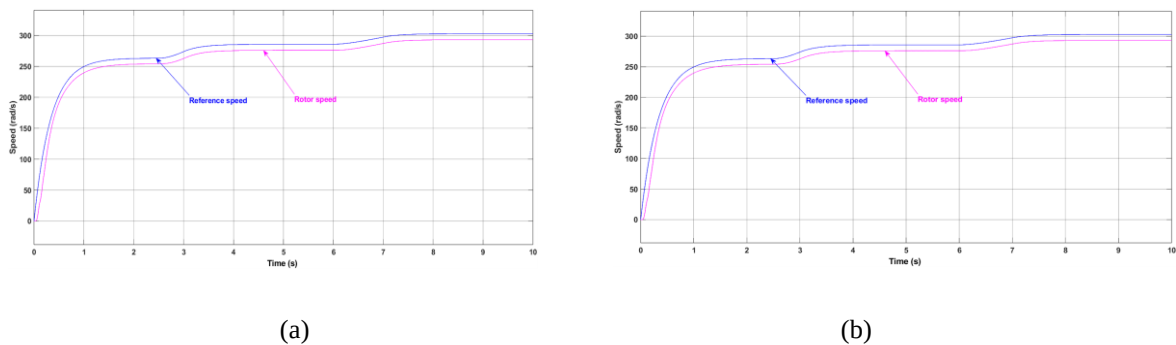


Figure 6. Rotor and reference speed,
(a)The proposed method, (b) The alternative configuration

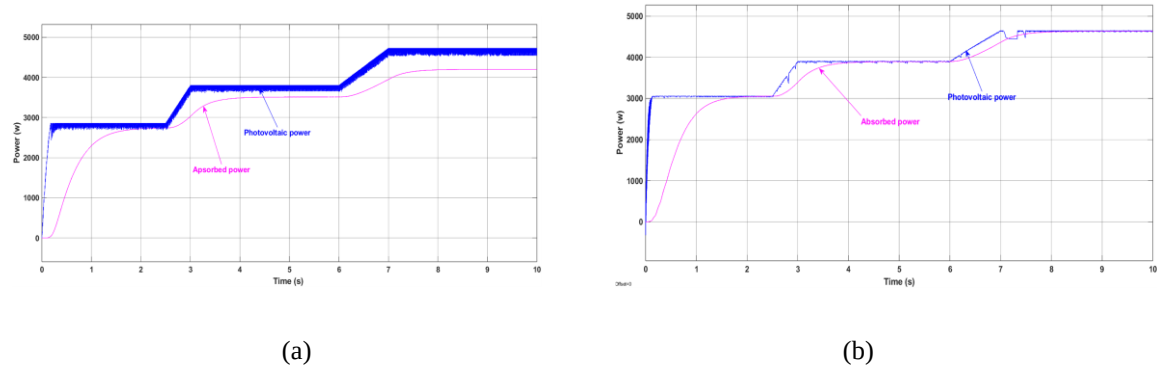


Figure 7. Photovoltaic and absorbed power,
(a)The proposed method, (b) The alternative configuration

III. Conclusion

Stand-alone solar pumping system are more suitable compared to other systems and for getting the best from this system using DSIM to drive the centrifugal pump, two control strategy based on P&O MPPT algorithm and deferent configuration of IRFOC discussed in this paper, implementing the IRFOC is usually used with the feedback current and PI controllers, this controller is powerful in the study state performance and ensuring accurate speed control and that improve the efficiency of the system but due to tier weakness related to dynamic reference the torque response have an important ripple value consequently overheating the motor thus reducing the lifespan of the system and it more likely to fail sooner, unlike the second method that replace the feedback and current regulator with estimation based on mathematical equation that reduce the complexity of the control technique and while it not rely on current feedback the approach is less sensitive to the parameter variation, and with the lower torque ripple that made the motor operation more smoother and improving the reliability of the system however the power losses is considerable compared to the first method. In the next research, we will focus on improving the control strategy to make the system more flexible and robust to perturbations and enhancing the performance of the system with a control technique that improves the efficiency without sacrificing the reliability in order to achieve the optimal performance from the system.

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