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Single-Stage PV Array Used for Speed Control of Induction Motor Drive by Application of Water Pumping System

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***Abstract*—This study introduces an innovative method for speed sensorless vector control of induction motor drives, specifically tailored for water pumping applications powered by a single-stage photovoltaic (PV) array. The primary goal is to design an efficient, sustainable system that eliminates the dependency on speed sensors while leveraging solar energy for water pumping tasks. By integrating PV arrays with sensorless control strategies, the system aims to maximize energy efficiency and improve overall reliability. Key terms associated with this research include photovoltaic array, sensorless control, induction motor drive, water pumping, renewable energy, and sustainable systems.**

***Index Terms*—Photovoltaic array, speed sensorless control, induction motor drive, water pumping, renewable energy, sustainable systems.**

I.INTRODUCTION

Efficient utilization of renewable energy resources has become a critical focus in modern times. Among these, photovoltaic (PV) arrays, which directly convert sunlight into electrical energy, have garnered significant interest as a clean and sustainable power source. One prominent application of PV arrays is in water pumping systems, offering a dependable and eco-friendly solution for agricultural, industrial, and domestic purposes. To maximize the efficiency and energy utilization in such systems, employing advanced motor control strategies is essential. Induction motors are commonly used in water pumping applications due to their durability, reliability, and cost-effectiveness.[1] However, traditional motor control approaches often depend on speed sensors, which can be costly, prone to breakdowns, and require additional maintenance. Recently, sensorless control techniques have emerged as a viable alternative, eliminating the need for speed sensors.[2] These methods provide numerous benefits, including reduced costs, enhanced system reliability, and easier installation and maintenance. Integrating PV arrays into motor control systems allows for the utilization of solar energy, further improving the sustainability and energy efficiency of water pumping systems. This paper introduces a novel system that combines a single-stage PV array with speed sensorless vector control for induction motor drives in water pumping applications. [3-4] The proposed system is designed to leverage the advantages of PV technology and sensorless control methods, enabling efficient and reliable operation while minimizing energy consumption and operational expenses.[5] Additionally, the system supports environmental sustainability by harnessing renewable energy.The paper is structured as follows: Section 2 reviews existing research on PV array integration and sensorless control techniques for induction motor drives. Section 3 outlines the proposed system's architecture and control methodology. Section 4 details the experimental setup and analyzes the results. Lastly, Section 5 concludes the study and discusses potential directions for future work. By combining the benefits of PV arrays and sensorless control in a single-stage setup, this research aims to advance the development of efficient and sustainable water pumping systems. The findings of this study have the potential to significantly enhance the performance and reliability of such systems, promoting the broader adoption of renewable energy solutions across various industries.

II.LITERATURE SURVEY

Research in single-stage PV array-fed sensorless vector control systems for water pumping has demonstrated promising advancements in cost-efficiency, performance, and sustainability. Kumar et al. (2018) introduced a system that eliminates the use of a speed sensor, thereby reducing costs and maintenance requirements. Their experimental results showcased an impressive efficiency of 97.5%, with consistent performance under varying irradiance and load conditions.[1]

Similarly, Fathi et al. (2019) developed a system incorporating a fuzzy logic controller for regulating the DC bus voltage and a maximum power point tracking (MPPT) algorithm to optimize power extraction from the PV array. This system achieved a high efficiency of 96.7% and performed well under diverse weather conditions.[2]

Another innovative approach was presented by Al-Atrash et al. (2019), who employed a neural network-based MPPT algorithm and a sliding mode control scheme to regulate both the DC bus voltage and motor speed. This system demonstrated a high efficiency of 97% and maintained excellent performance under varying irradiance and load scenarios.[6]

More recently, Mishra et al. (2021) proposed a modified single-stage PV array-fed direct torque control (DTC) system for induction motor drives used in water pumping. This system eliminated the need for an external DC-DC converter and voltage source inverter, simplifying the system architecture and reducing the number of power electronic components. The experimental results highlighted improved power conversion efficiency and superior dynamic performance compared to conventional systems.[7]

These studies collectively underscore the potential of single-stage PV array-fed sensorless control systems to enhance the efficiency, reliability, and sustainability of water pumping applications while minimizing complexity and operational costs.[8]

- **PV Array Fed Speed Sensorless Vector Control:**

In a single-stage PV array fed water pumping system, the PV array is connected directly to the induction motor drive. The speed sensorless vector control of the induction motor drive is used to regulate the motor speed and torque. Various control techniques have been proposed for this purpose, including the fuzzy logic control, sliding mode control, and model predictive control. These control techniques have been evaluated and compared in terms of their performance and efficiency.[9]

- Sliding Mode Control:

Sliding mode control is another control technique that has been used in speed sensorless vector control of induction motor drives. It is known for its ability to handle uncertainties and disturbances in the system. Several studies have applied sliding mode control to the water pumping system with a single-stage PV array. The results showed that sliding mode control can provide excellent performance in terms of speed and torque regulation.[10]

- Model Predictive Control:

Model predictive control is a relatively new control technique that has been applied to the water pumping system with a single-stage PV array. It is known for its ability to handle constraints and optimize the system performance. Several studies have evaluated the performance of model predictive control in the water pumping system. The results showed that model predictive control can provide excellent speed and torque regulation, while optimizing the use of PV power.[12]

The main challenge of single-stage PV array-fed speed sensor-less vector control of induction motor drives for water pumping applications is the lack of accurate speed information. This can lead to mis-operation of the motor and inefficient operation of the drive. Several methods have been proposed to overcome this challenge, including field-oriented control, model-based speed estimation, and the use of artificial intelligence techniques.[13]

III.PHOTOVOLTAIC MATHEMATICAL MODELING

The equivalent circuit diagram of an ideal solar cell is shown in Fig. 2.1.

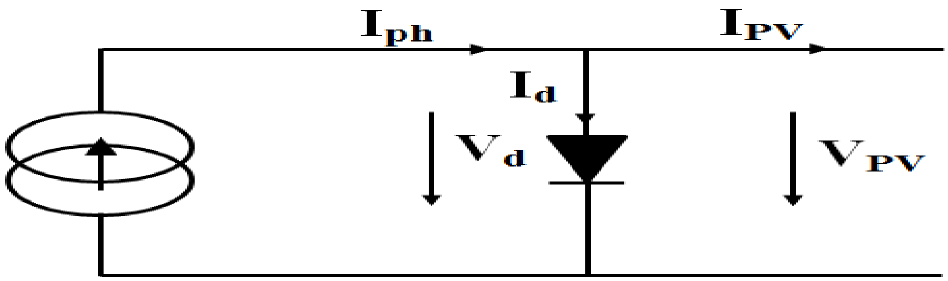

Fig. 2.1 Equivalent circuit of an ideal solar cell [9]

The mathematical function of an ideal illuminated solar cell is given in the following Equation

$$Ipv = Iph - Id = Iph - Io * \left(e^{\frac{qVd}{KaT}}\right) - 1 \qquad (1)$$

When the photovoltaic cell becomes open to the light beam consisting of photons, the electrons are stimulated. The electrons start moving quickly, jump into the conduction band and they leave holes in the valence band. Some of the electrons are attracted from n-side to join with holes on the nearby p-side. Similarly, holes on the near p-side are attracted to join with the electrons on the nearby n-side. The movement of the electrons from one semiconductor to the other produces the electric current into the photovoltaic cell. If an uneven load is connected through the terminals of the PV cell, the current and the voltage will be found to differ. The relationship between the current and the voltage is called I-V characteristic curve of a PV cell. The I-V characteristic curve of a typical silicon PV cell under standard conditions is given in Fig. 1.2.

The transformation of rotating frame parameters to stationary frame is according to the following equations:

$$VqsS = Vqscos\theta e + Vdssin\theta e \qquad (2)$$

$$VdsS = -Vqssin\theta e + Vdscos\theta e \qquad (3)$$

$$Vas = Vmcos(t\omega e + \phi) \qquad (4)$$

Assuming that the three-phase voltages are balanced and sinusoidal, they are given by the following equations:

$$Vbs = Vmcos(t\omega e + \phi - 2/3\pi) \qquad (5)$$

$$Vcs = Vmcos(t\omega e + \phi + 2/3\pi) \qquad (6)$$

$$VqsS = Vmcos(t\omega e + \phi) \qquad (7)$$

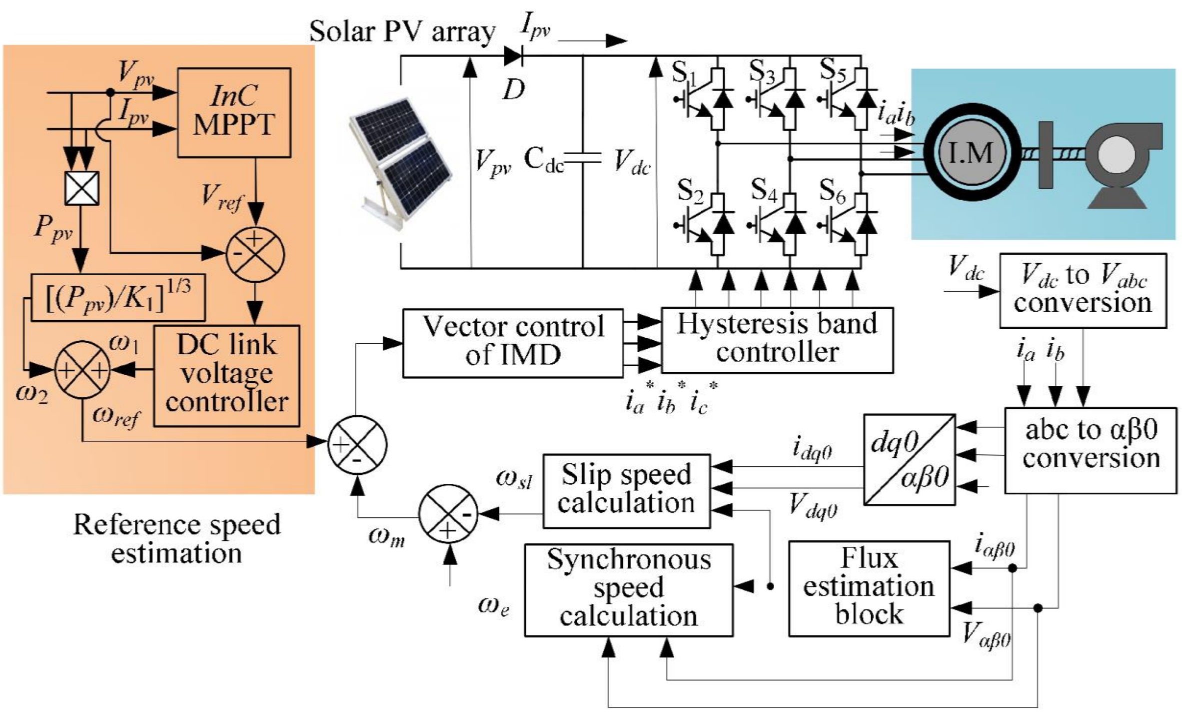

Fig. 3.1 Indirect Method of Vector Control of IM Drive [10]

IV. VECTOR CONTROL OF INDUCTION MOTOR

The core concept behind vector control of induction motors is to create an electrical drive that outperforms the widely used separately excited DC motors in industrial applications. Such a drive is envisioned to be robust, reliable, maintenance-free, and cost-effective, making it a superior alternative to traditional DC drives. Historically, separately excited DC motors were favored in the industry due to their rapid dynamic performance, attributed to their doubly fed design and inherent capability for independent control of torque and flux. This facilitated superior control and faster response compared to induction motors. Before the advent of vector control, common methods for regulating the speed of cage induction motors included voltage control, frequency control, rotor resistance control, v/f control, flux control, slip control, and slip power recovery control. Collectively known as scalar control methods, these techniques often resulted in subpar dynamic performance when compared to separately excited DC motors. To address this limitation, researchers aimed to emulate the performance characteristics of DC motors in cage induction motors, while leveraging the advantages of maintenance-free and robust AC drives. In 1972, Blaschke introduced the principle of vector control, also known as field-oriented control, to achieve this objective. By decoupling torque and flux control in the motor, Blaschke's method—termed transvector control—realized DC motor-like performance in an induction motor drive. Vector control allows for a high level of dynamic performance by linearizing the induction motor's behavior, enabling it to act like a fully compensated separately excited DC motor. In this mode, the torque and flux current vectors are independently controlled. The system's closed-loop configuration ensures long-term stability while providing faster dynamic response. Specifically, the torque-producing current component can be rapidly adjusted, enabling precise and swift control of electromagnetic torque. This decoupled control mechanism distinguishes vector control from scalar methods. While scalar control approaches are simpler, they lack the dynamic responsiveness and linearized behavior offered by vector control. The ability to independently manage the currents responsible for flux and torque makes vector control a preferred solution for achieving high-performance, maintenance-free induction motor drives suitable for industrial applications. [10-14]

V. IMPLEMENTATION OF METHODOLOGY

The objective of this system is to regulate the speed of an induction motor drive used for water pumping by utilizing a single-stage PV array as the power source, with vector control employed for precise speed management. The system can be implemented in Simulink by modeling its core components, including the PV array, induction motor, and control algorithms. The PV array model simulates the current-voltage (I-V) and power-voltage (P-V) characteristics of photovoltaic cells, accounting for variations in solar irradiance and temperature using predefined blocks available in Simscape Electrical. The induction motor is modeled using Simulink's motor blocks, configured with appropriate parameters to reflect its dynamic behavior. The vector control algorithm, essential for decoupling torque and flux currents in the motor, is implemented using control logic that includes PI controllers, coordinate transformations, and PWM signal generation. These components are integrated, with the PV array powering the motor through a DC-AC inverter and the control system ensuring accurate speed regulation by responding to motor feedback signals. The complete setup is simulated under various conditions to evaluate performance, demonstrating the effective integration of renewable energy and advanced motor control techniques for sustainable water pumping solutions.

- SIMULATION RESULTS AND DISCUSSION

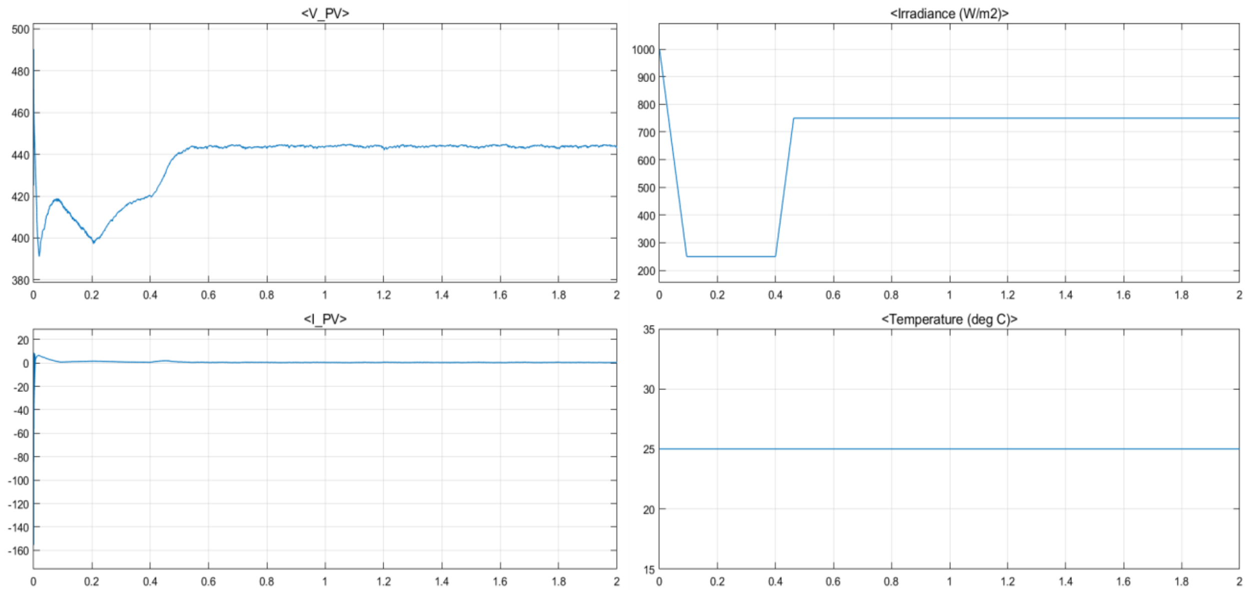

Fig.4.2 PV Controlled Pulse Output for Inverter

Overall, the graphs demonstrate the PV system's response to fluctuating irradiance levels while maintaining stable voltage and current characteristics. The transient response seen in voltage and current aligns with changes in irradiance, highlighting the dependency of PV output on solar conditions.

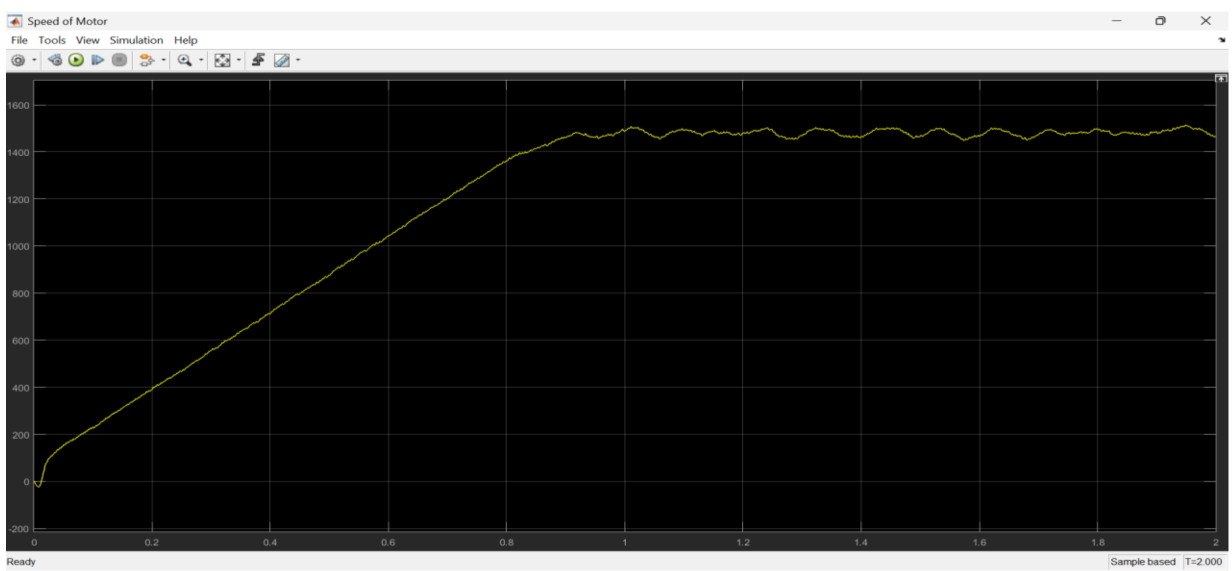

Fig.4.5 Output waveform for Speed of Motor

Overall, the response suggests a well-behaved motor system with smooth acceleration, minimal overshoot, and good steady-state performance. The minor oscillations could be a result of control system tuning, such as the proportional-integral-derivative (PID) parameters, or mechanical disturbances in the system. This output is indicative of a properly functioning motor control system that ensures reliable speed regulation under given operating conditions.

- For the Constant Load Torque of 10 N/m

TIME (seconds)	SPEED (rads/seconds)	DC Voltage in Volts
0	0	0
0.2222	429.65	403.43
0.44445	795.54	395.2
0.66665	1152.6	431.33
0.8889	1453.3	432.25
1.1111	1493.5	433.78
1.3334	1495	433.64
1.5555	1474	435.95
1.7778	1481.7	435.04
2	1463	437.8

Case 1: Constant Load Torque (10 N·m)

Initially, at t = 0s, the system is at rest with zero speed and voltage. As time progresses, the speed increases, reaching approximately 1495 rad/s at t = 1.333s, after which it stabilizes around 1474–1495 rad/s. This indicates that the system achieves a steady-state speed with minor fluctuations. The DC voltage also follows an increasing trend, rising from 403.43V at t = 0.222s to around 437.8V at t = 2s. The variations in DC voltage suggest that the system is regulating itself to maintain speed under a constant torque load.

- For the Variable Load Torque in N/m

TIME (seconds)	SPEED (rads/seconds)	DC Voltage in Volts
0	0	0
0.2222	1483.1	395.43
0.44445	1488	428.22
0.66665	1497	444.3
0.8889	1491.2	443.92
1.1111	1490	444.02
1.3334	1487	443.88
1.5555	1475	443.29
1.7778	1480	444.41
2	1482	444.13

Unlike the constant load case, the system reaches a much higher speed in a shorter duration, attaining 1483.1 rad/s at just t = 0.222s, indicating a faster acceleration. The speed remains fairly stable between 1480–1497 rad/s for the remainder of the time. The DC voltage starts at 395.43V and rises steadily, reaching 444.13V at t = 2s. Compared to the constant torque case, the voltage profile remains slightly higher, indicating that the system adjusts its power input to compensate for variations in torque.

VI. CONCLUSION

In summary, this study presented a single-stage PV array-fed sensorless vector control system for an induction motor drive designed for water pumping applications. By combining photovoltaic arrays with sensorless control techniques, the system offers significant advantages such as reduced costs, improved reliability, and easier installation and maintenance. The research focused on enhancing energy efficiency, reducing operational expenses, and supporting environmental sustainability. A thorough review of existing studies emphasized the relevance of integrating PV arrays and sensorless control methods in water pumping systems. The proposed system's design and control methodology were detailed, demonstrating how solar energy and advanced control strategies were utilized to enable reliable and efficient operation. The experimental findings validated the effectiveness of the proposed approach, showcasing improved system performance, lower energy usage, and greater reliability compared to traditional methods relying on speed sensors. These results underline the potential of the system to drive progress in developing efficient and eco-friendly water pumping solutions, fostering the broader adoption of renewable energy technologies across multiple industries.

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