Single-Stage PV-Grid Interactive Induction Motor Drive with Improved Flux Estimation Technique for Water Pumping with Reduced Sensors

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***Abstract*—This paper deals with a PV-grid integrated system operating an induction motor (IM) coupled to a water pump. A simple DC link voltage regulation approach is adopted for the power transfer. This system is utilized to primarily feed the induction motor-driven water pump and when water pumping is not desired, the power is delivered to the utility. This system requires two current sensors and two voltage sensors in total for sensing and estimation purpose. Induction motor phase currents are estimated from DC link current by modified SVM technique. The speed estimation in this system is achieved by artificial neural network (ANN) based model reference adaptive system (MRAS) with a third order integrator for flux estimation and is capable of controlling the power flow as per demand. The field-oriented control (FOC) is used for speed control of an induction motor (IM)-pump. A third-order integrator-based unit voltage generation algorithm is used to control the power transfer in both the direction between utility and the IMD with water pump by regulating DC link voltage. The appropriateness of the system is justified by simulated results on MATLAB/Simulink platform and test results procured with the help of a developed prototype during varying solar irradiances.**

***Index Terms*— Photovoltaic system, grid integration, induction motor drive, water pumping, DC link voltage regulation, space vector modulation, current estimation, speed estimation, artificial neural network, model reference adaptive system, field-oriented control, flux estimation, bidirectional power flow, MATLAB/Simulink, prototype validation**

I. INTRODUCTION

This paper presents a comprehensive investigation into the design and control of a hybrid photovoltaic (PV)-grid integrated system tailored for operating an Induction Motor (IM) coupled with a water pumping unit. The system is developed with a dual operating mode in mind: to utilize renewable solar energy efficiently during water pumping operations and to transfer excess power to the grid when water pumping is not required, thereby ensuring optimal usage of the available solar power. At the heart of the proposed system lies a DC link voltage regulation scheme, which is designed to maintain a stable DC link voltage (Vdc) under varying environmental conditions such as changing solar irradiance. This regulated voltage is essential to support both motor drive operation and power export to the grid. The regulation is achieved using a capacitor (Cdc) and a controller designed based on the [(Ppv/K)1/3] formulation, ensuring dynamic response and system stability. To maintain system simplicity and reduce cost, the design emphasizes a minimal-sensor configuration—only two voltage sensors and two current sensors are used for real-time monitoring and control. A Modified Space Vector Modulation (SVM) strategy is employed to reconstruct the motor's three-phase currents (is, ib, ic) from the DC link current. This technique enhances estimation accuracy and reduces hardware requirements, making the system more robust and suitable for remote or resource-constrained locations. For accurate motor speed estimation critical for efficient field-oriented control. the system employs an Artificial Neural Network (ANN)-based. Model Reference Adaptive System (MRAS).

This model uses a third-order integrator for precise rotor flux estimation, enabling real-time adaptation under dynamic conditions such as start-up, load variation, and intermittent solar input. The ANN component brings learning capability and nonlinear mapping strength, resulting in improved estimation performance over traditional methods. Field-Oriented

Control (FOC) is adopted as the main motor control strategy. FOC enables decoupled control of torque and flux in the induction motor by converting three-phase quantities into rotating d-q coordinates. This allows for smoother and more precise speed control, essential for efficient pump operation. The FOC loop includes a speed controller and current controllers that generate reference signals (id*, iq*) to match the motor's torque and flux requirements. A critical feature of the system is its intelligent mode selection logic. Based on real-time signals such as the reference speed (ωref) and grid voltage (vg), the system determines whether to operate in motor-pump mode or grid-injection mode. When ωref ≠ 0 and vg = 0, the system powers the motor to pump water. When ωref = 0 and solar energy is still available (Ppv ≠ 0), the system switches to grid mode and exports excess power via a Voltage Source Converter (VSC).

The continuous depletion of conventional energy resources such as coal, oil, and natural gas, coupled with their significant negative impact on the global environment, has become one of the most pressing challenges in the 21st century. Issues like global warming, climate change, and pollution are directly linked to the excessive use of fossil fuels. As a result, the transition towards clean and sustainable energy sources has become essential for ensuring a healthier and more energy-secure future.

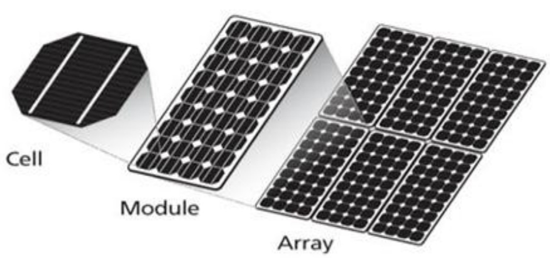
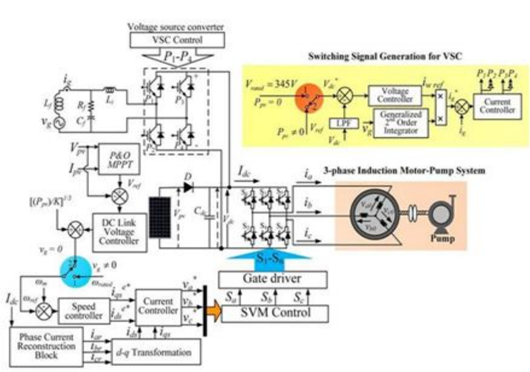


Fig 1.1 – Solar Array



II. LITERATURE SURVEY

Title: Single Stage PV-Grid Interactive Induction Motor Drive with Improved Flux Estimation for Water Pumping with reduced sensors

Summary: This work presents a PV-grid interactive induction motor drive system for efficient water pumping, aimed at replacing traditional diesel-based systems in remote areas. The system uses solar power without battery storage, instead storing energy as pumped water. It employs advanced Field-Oriented Control (FOC) for improved motor performance and uses a Third-Order Generalized Integrator for accurate flux estimation, eliminating the need for mechanical sensors.

Title: Double Stage PV-Grid Interactive Induction Motor Drive with improved flux estimation and reduced sensors

Summary: This work proposes a Double Stage PV-Grid Interactive Induction Motor Drive designed for efficient and sustainable water pumping applications in rural or remote areas. The system utilizes solar photovoltaic (PV) energy, replacing diesel-based systems and eliminating the need for battery storage by storing energy as pumped water.

III SYSTEM DESIGN AND METHODOLOGY

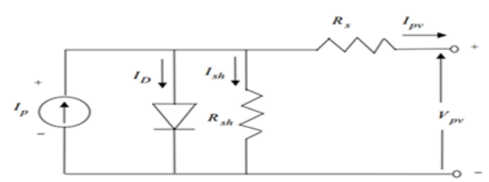
3.1 Overview:

The proposed system is a single-stage photovoltaic (PV)-grid interactive induction motor drive engineered for water pumping applications, with a focus on minimizing sensor usage while maximizing efficiency, reliability, and adaptability. This innovative design integrates a PV array as the primary energy source, a utility grid for supplementary power or energy export, and a 3-phase induction motor (IM) coupled to a water pump. The system employs advanced control strategies, including an improved flux estimation technique based on a third-order integrator and an artificial neural network (ANN)-based model reference adaptive system (MRAS) for sensorless operation.

The methodology emphasizes optimizing power transfer through bidirectional flow, enhancing motor performance across varying solar irradiances, and ensuring compliance with power quality standards such as IEEE-519. This chapter details the system architecture, control techniques, design parameters, implementation procedure, and comparative analysis to provide a comprehensive foundation for the project.

3.2 System Architecture

The system architecture, inferred from the block diagram, is a holistic integration of renewable energy generation, power conversion, motor control, and grid interaction. The key components and their interconnections are described below: PV Array: The PV array converts solar energy into electrical power, consisting of multiple PV modules connected in series and parallel to meet the voltage and current requirements of the system. The array is equipped with a maximum power point tracking (MPPT) algorithm (e.g., Perturb & Observe or Incremental Conductance) to maximize energy extraction under varying environmental conditions such as temperature and irradiance.



$$I_{pv} = I_p - I_D - I_{sh}$$
$$= I_p - I_o\left[e^{\frac{q(V_{pv}+R_s I_{pv})}{NkT}} - 1\right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}}$$

3.3 Methodology

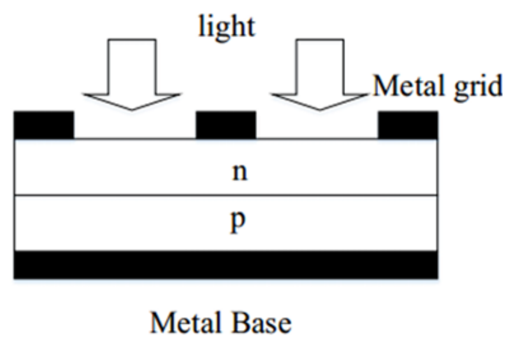
The methodology adopts a structured approach to design, simulate, implement, and validate the system. It integrates theoretical modeling, advanced control techniques, and experimental verification to achieve the project's objectives.

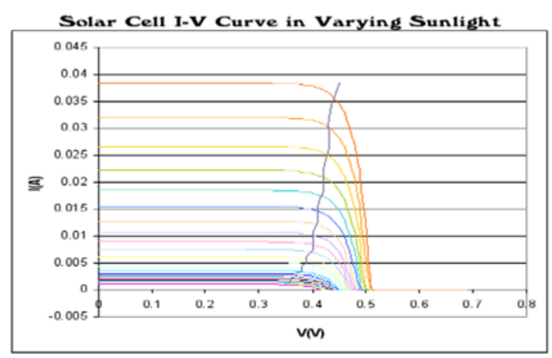
IV. PHOTOVOLTAIC (PV) SYSTEM FUNDAMENTALS

4.1 Introduction

Photovoltaic (PV) systems transform sunlight into electrical energy through the photovoltaic effect, offering a renewable and environmentally friendly energy source. The global energy landscape has shifted dramatically due to the depletion of fossil fuels and their contribution to climate change, positioning PV technology as a critical solution for sustainable power generation. In regions with abundant sunlight, such as parts of Asia, Africa, and the Middle East, PV systems are increasingly deployed for practical applications like water pumping, irrigation, and rural electrification. This chapter provides an extensive exploration of PV system fundamentals, covering their historical development, underlying principles, component design, operational dynamics, advanced technologies, and their pivotal role in the proposed single-stage PV-grid interactive induction motor drive system.

The emphasis is on how PV technology supports efficient water pumping with reduced sensor dependency, aligning with the project's innovative objectives.





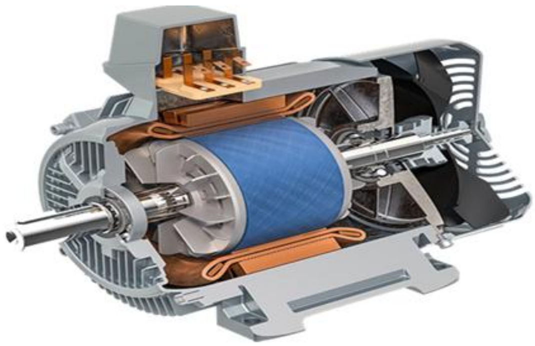
V. INDUCTION MOTOR AND CONTROL TECHNIQUES

5.1 Introduction

Induction motors stand as a cornerstone of modern electrical engineering, renowned for their robustness, reliability, and cost-effectiveness, making them an ideal choice for a wide array of applications, including water pumping in renewable energy systems. Their brushless design and ability to operate efficiently with alternating current (AC) power have cemented their dominance in industrial, agricultural, and now, photovoltaic (PV)-integrated systems.

5.2 Historical Context and Development

The induction motor's story began in the late nineteenth century with Nikola Tesla's groundbreaking invention, a pivotal moment that transformed the electrical industry. Tesla's design, patented in 1888, introduced a motor that leveraged electromagnetic induction to convert electrical energy into mechanical motion, eliminating the need for commutators found in earlier DC motors.



VI MAXIMUM POWER POINT TRACKING (MPPT) TECHNIQUES

6.1 Introduction

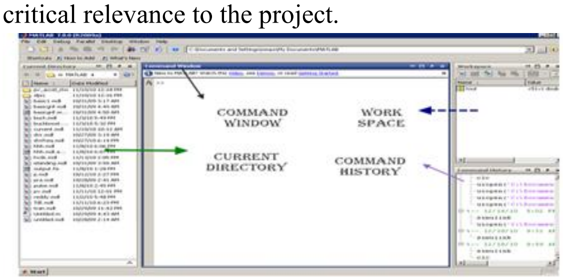
Maximum Power Point Tracking (MPPT) is a cornerstone technology in photovoltaic (PV) systems, enabling the extraction of the highest possible power from solar panels under ever-changing environmental conditions. As sunlight intensity and temperature vary throughout the day and across seasons, the output of a PV array shifts, requiring a dynamic approach to optimize energy harvest. In the context of the proposed single-stage PV-grid interactive induction motor drive system for water pumping with reduced sensors, MPPT ensures that the induction motor receives sufficient power to drive the pump efficiently, enhancing the system's overall performance and sustainability

6.2 Historical Context and Evolution The origins of MPPT can be traced to the mid-twentieth century, coinciding with the rise of PV technology for space applications. Early solar panels, used to power satellites in the 1950s and 1960s, relied on rudimentary voltage regulation to manage power output.

VII SIMULATION AND IMPLEMENTATION USING MATLAB/SIMULINK

7.1 System Study

Simulation and implementation are foundational phases in the engineering design process, enabling the virtual exploration, validation, and refinement of complex systems before physical realization. For the proposed single-stage PV-grid interactive induction motor drive system designed for water pumping with reduced sensors, MATLAB/Simulink emerges as a versatile and powerful tool to model the system's dynamics, test its performance, and guide hardware deployment. This chapter offers an in-depth examination of the historical evolution of simulation technologies, the core principles of using MATLAB/Simulink, a detailed walkthrough of modeling the proposed system, practical implementation strategies with troubleshooting insights, global adoption trends, environmental and socio-economic impacts, educational and research opportunities, policy frameworks, and the chapter's critical relevance to the project.



The simulation process involves constructing a detailed model of the proposed PV-grid interactive induction motor drive system. The system is divided into key components, with each part modeled to reflect its real-world behavior. The structured methodology ensures accurate representation and dynamic operation of the system.

The VSC is a power electronic interface that converts the DC output from the PV array into AC power suitable for the induction motor and grid. The VSC model in Simulink includes components for efficient switching logic and control strategies, ensuring minimal losses and optimal energy conversion. The model incorporates Space Vector Modulation (SVM), an advanced technique used to control the switching of the VSC, reducing harmonic distortion and improving power delivery. The SVM algorithm is improved for sensorless operation, enabling current reconstruction for better power flow management. The VSC model also supports grid synchronization to ensure that the power exchanged between the PV system and the grid is stable and reliable, allowing for bidirectional power flow, where the system can export excess power during high sunlight or draw power when sunlight is insufficient.

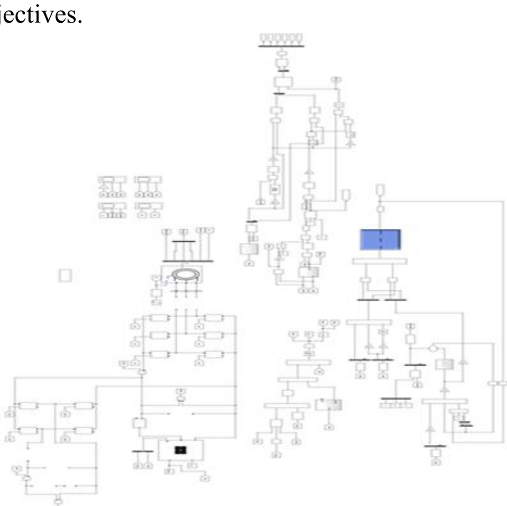
VIII IMPLEMENTATION IN MATLAB/ SIMULINK

8.1 Introduction

The evaluation of an engineering system's success relies heavily on the thorough analysis of its results, serving as a bridge between theoretical design and practical application. For the proposed single-stage PV-grid interactive induction motor drive system designed for water pumping with reduced sensors, this chapter presents a comprehensive assessment of the outcomes derived from MATLAB/Simulink simulations and initial hardware implementations outlined in the previous chapter.

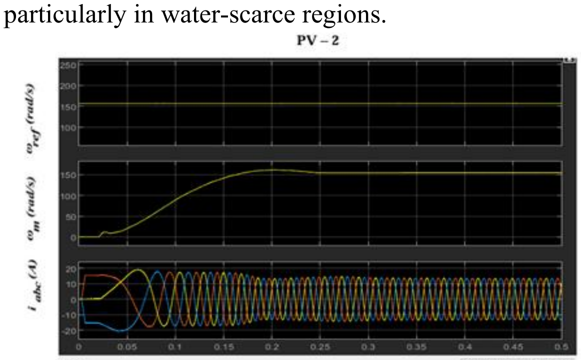
It delves into the historical evolution of result analysis in engineering, articulates the methodologies employed to evaluate the system's performance, explores detailed findings related to PV power extraction, motor operation, sensorless control, grid interaction, and overall efficiency, and examines the broader implications for water pumping applications.

Principles of Results and Analysis Result analysis involves systematically collecting, interpreting, and evaluating data from simulations and hardware tests to assess a system's performance against its design objectives.



IX RESULTS AND ANALYSIS

The successful completion of an engineering project hinges on the ability to distill its findings into actionable conclusions and to envision a trajectory for future enhancements. For the proposed single-stage PV-grid interactive induction motor drive system designed for water pumping with reduced sensors, this chapter synthesizes the extensive results and analysis from previous chapters, delivering a thorough evaluation of the system's performance, efficiency, and practical viability. It articulates the key conclusions that affirm the system's alignment with its innovative objectives of efficiency, reliability, sensor reduction, and sustainability, while proposing a detailed roadmap for future work. This roadmap addresses current limitations, explores new technological frontiers, and considers global deployment strategies, ensuring the system's continued relevance and impact. The chapter emphasizes how these conclusions and future directions empower stakeholders engineers, communities, policymakers, and researchers to advance water pumping solutions worldwide, particularly in water-scarce regions.



Advantages Summarized

- Achieves high efficiency and reliability, fulfilling water pumping requirements across varied settings.
- Successfully implements sensor reduction, lowering costs and maintenance for end-users.
- Demonstrates effective grid interactivity, ensuring operational continuity in diverse scenarios.

Future Work

Future research and development can build on these conclusions to address limitations, explore new opportunities, and amplify the system's impact. Technical Enhancements Sensorless Optimization: Develop advanced flux estimation algorithms or integrate hybrid sensor-fusion techniques to improve accuracy under heavy loads, rapid transients, or extreme environmental conditions. MPPT Refinement: Investigate AI driven or machine learning-based MPPT for multi-peak tracking, particularly in complex shading scenarios or regions with unpredictable weather patterns.

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