



Solar Powered Variable Frequency Drive for Efficient Agricultural Water Pumping

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ABSTRACT: Solar powered water pumping systems offer a sustainable alternative to conventional grid-connected and diesel-driven irrigation systems. However, fixed-speed solar pumping systems suffer from poor energy utilization under varying solar irradiance. This paper presents the design and analysis of a solar photovoltaic (PV) based water pumping system integrated with a Variable Frequency Drive (VFD) for efficient agricultural irrigation. The proposed system employs a mono-crystalline PV array to supply a solar-compatible VFD, which drives a three-phase induction motor coupled to a centrifugal or submersible pump. A scalar V/f control strategy is implemented to regulate the motor speed according to the available solar power. System sizing, mathematical modelling and performance analysis are presented. The results show that the proposed solar PV–VFD pumping system improves energy utilization, reduces mechanical and electrical stresses, and enhances operational reliability compared with conventional pumping systems.

Keywords: Solar Photovoltaic (PV) System, Variable Frequency Drive (VFD), Water Pumping System, Agricultural Irrigation, Induction Motor Drive, V/f Control Strategy, Renewable Energy, Solar Irradiance, Energy Efficiency, Sustainable Irrigation.

1. Introduction

Agriculture is one of the largest consumers of electrical energy and water resources, particularly in developing countries. In India, irrigation pumping systems are predominantly operated using grid-connected induction motors or diesel engines. These conventional systems suffer from unreliable power supply, frequent voltage fluctuations, increasing fuel costs and significant environmental pollution.

Solar photovoltaic (PV) energy has emerged as an attractive alternative for agricultural pumping due to its availability, modularity and low operating cost. However, conventional solar pumping

systems generally operate at fixed speed and cannot effectively utilize the available solar power under varying irradiance conditions. As a result, frequent pump shutdowns and poor energy matching occur. The integration of a Variable Frequency Drive (VFD) with a solar powered pumping system enables variable-speed operation of the induction motor and allows effective matching between the available PV power and the hydraulic load. This paper proposes a solar powered VFD based water pumping system and presents its system architecture, analytical formulation and performance evaluation.

2. Objectives

The main objective of this project is to design a standalone solar-powered water pumping system using Variable Frequency Drive (VFD) technology. The system operates independently using solar energy, reducing dependence on grid electricity and diesel fuel. Another objective is to control the speed of a three-phase induction motor based on the available solar power. The VFD adjusts motor speed according to variations in solar energy to ensure efficient operation. Reducing energy losses during motor startup and partial load operation is also a key objective. Soft starting and speed control using VFD help minimize power losses and motor stress. Finally, the economic and environmental benefits of the proposed system are studied to highlight cost reduction and eco-friendly operation.

3. Related Work

Several researchers have investigated solar PV based water pumping systems using induction motor drives. Previous studies have reported that variable-speed operation significantly improves system efficiency and reliability under fluctuating solar conditions. The application of VFDs enables soft starting, reduced inrush current and continuous speed adaptation.

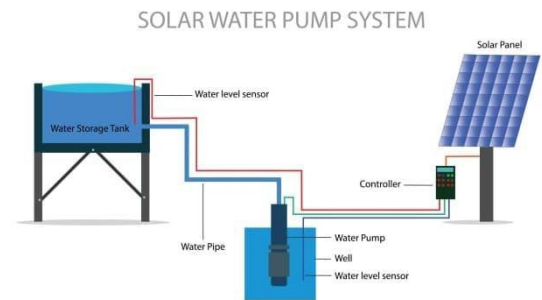
Advanced control techniques such as optimized scalar control and artificial intelligence based controllers have been proposed to enhance the performance of PV driven pumping systems. However, due to simplicity and robustness, scalar V/f control remains widely adopted for practical agricultural applications. The literature clearly establishes that VFD controlled solar pumping systems provide better energy utilization and lower operating cost compared with fixed-speed systems.

4. System Architecture

4.1 Proposed System Configuration

The proposed system consists of the following major components:

- Solar PV array
- DC protection and DC-link stage
- Solar compatible VFD with PWM inverter
- Three-phase induction motor
- Centrifugal or submersible pump



The PV array supplies DC power directly to the VFD. The VFD converts the DC input into a controlled three-phase AC output with variable voltage and frequency. The induction motor drives the pump, which delivers water to the irrigation network.

4.2 Operating Principle

The VFD controller implements a scalar V/f strategy to regulate the inverter output. The motor speed is continuously adjusted according to the available solar power. During high irradiance, the motor operates near rated frequency, while under reduced irradiance the motor speed is lowered instead of stopping the pump. Soft-start operation reduces electrical and mechanical stress.

5. Results and Discussion

The performance analysis shows that the proposed solar PV–VFD pumping system achieves superior energy utilization compared to fixed-speed pumping systems. Soft starting reduces the starting current significantly and minimizes mechanical shock to the pump and motor.

Variable-speed operation allows the pump to operate closer to its best efficiency point throughout the day. Based on pump affinity laws, a 20% reduction in speed results in nearly 50%

reduction in power consumption while still providing sufficient discharge for irrigation. The mono-crystalline PV modules exhibit lower temperature related power degradation, making the system suitable for high-temperature agricultural environments. The proposed system eliminates fuel consumption, reduces greenhouse gas emissions and improves water-use efficiency, especially when integrated with drip irrigation networks.

6. Preparation of Figures and Tables

Fig 1.illustrates a Architecture of Solar-Powered Water Pumping System that utilizes a Variable Frequency Drive (VFD) to bridge the gap between renewable energy generation and mechanical output. The process begins with the PV (Photovoltaic) Array, which captures solar energy and converts it into electrical power. While the diagram denotes a "PV Array with Inverter," the power is typically channelled into the VFD system to ensure the motor operates efficiently under varying sunlight conditions.

The heart of the operation lies within the Variable Frequency Drive (VFD), a power electronics device designed to control the speed and torque of the motor. Initially, the Rectifier converts the incoming power into DC, which is then smoothed by the DC bus with filter to eliminate ripples and voltage spikes. To achieve precise control, a Potentiometer provides a manual speed reference to the Controller. This controller uses Pulse Width Modulation (PWM) a high-speed switching technique to dictate how the Inverter should reconstruct the power. The Inverter then converts the filtered DC back into a variable-frequency AC output. By adjusting the frequency (f) and voltage, the system can directly control the motor's RPM, ensuring the pump doesn't stall during low-light periods (like early morning or cloud cover) and operates at peak performance during high-noon.

Finally, this regulated AC power is delivered to the Motor pump set. Unlike a standard "on/off" system, this VFD-based approach allows for a

"soft start," reducing mechanical wear and tear on the pump's internal components. This setup is highly efficient for agricultural and industrial applications because it maximizes the water discharge per watt of solar energy harvested, providing a sustainable and automated solution for water management without the need for a constant grid connection.

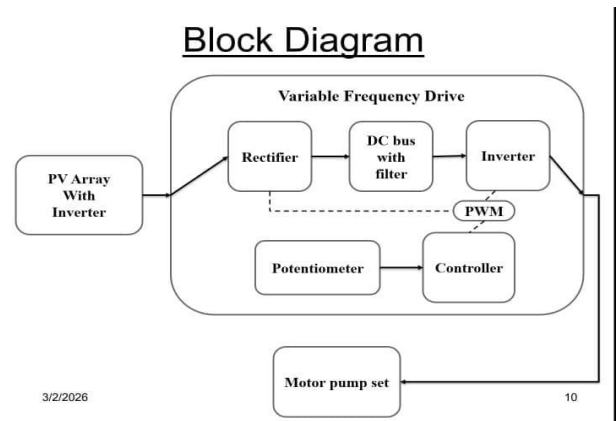


Figure 1: Block Diagram

7. Mathematical Modelling and Derivations

7.1 Induction Motor Speed Relation

The synchronous speed of an induction motor is given by

$$N_s = \frac{120f}{P} \text{ (rpm)}$$

where f is the supply frequency in Hz and P is the number of poles.

The rotor speed is

$$N = N_s(1-s)$$

where s is the slip.

Hence, motor speed is directly proportional to the inverter output frequency.

7.2 V/f Control Principle

The air-gap flux of an induction motor is approximately expressed as

$$\Phi \propto \frac{V}{f}$$

Where V is the stator phase voltage and f is the supply frequency.

To maintain constant air-gap flux,

$$\frac{V}{f} = \text{constant}$$

This ensures stable torque production, prevents magnetic saturation and avoids excessive core losses.

7.3 Pump Affinity Laws

For a centrifugal pump operating at speed N ,

$$Q \propto NH \propto N^2 P \propto N^3$$

Where Q is the discharge, H is the head, and P is the hydraulic power.

These relations demonstrate that a small reduction in motor speed produces a large reduction in power consumption.

7.4 PV Array Power Requirement

The required PV input power is given by

$$P_{PV} = \frac{P_m}{\eta_m \eta_{VFD}}$$

Where P_m is the motor rated mechanical power, η_m is the motor efficiency, and η_{VFD} is the VFD efficiency.

7.5 Daily Energy Generation

The daily energy produced by the PV array is

$$E_{day} = P_{PV,inst} \times H_{psh} \times \eta_{sys}$$

Where $P_{PV,inst}$ is the installed PV capacity, H_{psh} is the average peak sun hours, and η_{sys} is the overall system efficiency.

7.6 Inverter Output Voltage Relation

For linear PWM operation,

$$V_{ph} \propto mV_{dc}$$

Where V_{ph} is the fundamental phase voltage, m is the modulation index, and V_{dc} is the DC-link voltage.

8. System Design and Implementation

The proposed system is designed for a 3 HP induction motor. Considering motor efficiency of

85% and VFD efficiency of 95%, the required electrical input power is approximately 2.77 kW. A 3.5 kW mono-crystalline PV array is selected to compensate for temperature, dust and conversion losses.

The VFD operates over a frequency range of 0–50 Hz and supplies a three-phase output of 380–415 V. The induction motor drives a centrifugal or submersible pump depending on the water source. Variable-speed operation enables smooth and continuous pumping under fluctuating solar irradiance.

9. Conclusion

This paper presented a solar photovoltaic based water pumping system integrated with a Variable Frequency Drive for agricultural irrigation. The proposed architecture enables efficient utilization of solar energy by dynamically matching motor speed with available PV power. Scalar V/f control ensures stable motor operation, reduced losses and extended equipment life. Analytical derivations and system design confirm that the proposed system is technically feasible and economically suitable for rural and off-grid irrigation applications.

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