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Analysis and Dynamic Modelling of a Solar Water Pumping System

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Abstract

Bangladesh faces a persistent energy crisis despite its abundant solar irradiation of 4.5 kWh/m² per day. Rural electrification efforts have achieved limited success due to high costs and infrastructural constraints. This paper proposes a sustainable and cost-effective DC photovoltaic (PV) water pumping system designed to address irrigation demands in rural areas. By directly connecting a PV array to a DC water pump, the system avoids the need for an inverter, significantly reducing both initial and operational costs. The system incorporates Maximum Power Point Tracking (MPPT) to optimize energy utilization, a DC-DC boost converter to enhance current delivery, and a battery to ensure reliable operation during inconsistent sunlight conditions. All components are locally sourced, minimizing costs and ensuring accessibility for underserved communities. Preliminary analysis highlights the system's high efficiency and ability to meet irrigation requirements during peak seasons. The modular design also enables scalability for broader applications, including domestic water supply and small-scale industrial use. This approach offers a low-maintenance alternative to conventional diesel or AC-powered systems, enhancing energy independence and agricultural productivity in rural regions. By leveraging locally available resources and incorporating advanced energy management techniques, the proposed design exemplifies the transformative potential of solar energy to address the energy-water nexus in developing nations. Future work will explore further optimization and integration of IoT-based monitoring for real-time system performance tracking and maintenanc**e.**

Keywords:
Photovoltaics (PV), MPPT, Renewable Energy, Water Pumping System, Flow Rate and Speed Comparison.

1. Introduction
In many regions worldwide, including Bangladesh, the availability of water and energy is becoming an increasingly critical concern. In areas without access to electric utilities, traditional methods for water extraction—such as surface water sources or mechanical pumps—have remained largely unchanged for decades (Khan 2012). As the demand for both higher water quantities and improved water quality, alongside lower operational costs, enhanced reliability, and growing environmental concerns, continues to rise, many agricultural and livestock producers are seeking alternative technologies for remote water pumping. One such solution is direct-coupled solar photovoltaic (PV)-powered systems, which are gaining popularity in rural areas of Bangladesh due to the abundance of sunny days (Biswas 2018).

Given the growing urgency of addressing environmental issues like global warming, there is a strong motivation to develop and adopt renewable energy sources, including solar energy systems. However, one of the key challenges faced by standalone PV systems is their efficiency and performance under varying environmental and operational conditions. This paper presents the analysis and simulation of a solar water pumping system powered by a brushless DC motor. The performance of PV-powered water pumping systems, particularly in remote and off-grid areas, is often constrained by fluctuations in solar irradiation and ambient temperature. This research explores these challenges and offers solutions for improving system efficiency under such conditions.

The model developed in this study simulates a solar water pumping system composed of individual components, including the PV modules and brushless DC motor. The simulation results indicate that the efficiency of the solar PV water pumping system improves significantly when compared to existing systems, especially under variable environmental conditions (Shebani 2017). The performance of standalone PV systems is highly dependent on the configuration of the PV modules—whether they are connected in series, parallel, or a combination of both. This study also examines the impact of these configurations on system performance, showing that achieving optimal matching of modules becomes more difficult under low solar irradiation. However, a well-chosen combination of series and parallel connections can enhance system efficiency. Furthermore, the performance of solar water pumping systems with both fixed-position and manually tracked PV panels is assessed. The results demonstrate that a manually tracked system can achieve up to 22.6% greater efficiency compared to systems with fixed-position PV panels(Masters 2013). Energy scarcity remains one of the most pressing global challenges. In Bangladesh, a developing country, only 47% of the population has access to electricity, with the per capita energy consumption averaging just 220 kWh (Biswas 2018). This energy deficit has significant implications for agricultural productivity, which in turn affects the nation's overall economic growth. Despite having fertile soil and favorable agricultural conditions, Bangladesh's agricultural sector struggles to meet the demands of its population due to the gap between energy supply and demand. The implementation of solar photovoltaic panels for irrigation could play a transformative role in bridging this gap, offering a sustainable and reliable energy source for agriculture and improving food security.

1.1 Objectives
The main objective of this research is to conceptualize, develop, and design a solar-based water pumping system for irrigation and other applications. The secondary objectives of this study are:
To establish a novel methodology for the design of solar-powered water pumping systems.
To explore the basic principles behind solar-based water pumping systems.
To assess the current status and potential of power production from solar irradiance.
To reduce fuel consumption in irrigation systems.
To alleviate the reliance on grid electricity for water pumping.

2. Literature Review

Solar photovoltaic water pumping systems (SPVWPS) have been a subject of research for over 50 years. In the early 1970s, studies were conducted to explore the feasibility, viability, and economics of using SPVWPS for water pumping (Sontake 2016). These systems consist of various components from different engineering disciplines, including mechanical, electrical, electronics, computer, control, and civil engineering. The interdisciplinary nature of SPVWPS has attracted researchers from diverse engineering domains, all contributing to improvements in system efficiency and cost-effectiveness to meet water pumping needs for human consumption, livestock, and irrigation. In rural areas, photovoltaic water pumping systems have become a viable solution for water supply, particularly in regions without access to an electric grid. In Bangladesh, where approximately 40% of the population lacks access to electricity, solar water pumping systems are an increasingly important and popular application of solar photovoltaic technology (Das 2021) Das et al. (Shukla 2020) optimized a hybrid energy system for the remote Bandarban region in Bangladesh, combining PV, biomass, hydro, and battery storage to meet off-grid energy demands. The study found that this hybrid system provided the most efficient solution with a cost of electricity (COE) of \$0.128/kWh and minimal CO_2 emissions of 17.6 kg/year.

The results were validated by comparison with other studies. In recent years, solar photovoltaic (PV) water pumping systems (PVPS) have gained significant attention due to their ability to provide sustainable water solutions in remote and rural areas, where access to electricity is limited (Chisthi 2020), (Meunier 2020). PVPS are seen as a promising alternative to traditional diesel or grid-based systems, particularly in regions with abundant solar irradiance, such as India and Bangladesh. These systems are cost-effective, with minimal operational costs, and they do not produce greenhouse gas emissions during operation, making them an environmentally friendly option (Subudhi 2019). A major challenge in PVPS is the non-linear relationship between the current and voltage of the PV array, which is affected by solar irradiance and temperature fluctuations. To overcome this, various Maximum Power Point Tracking (MPPT) techniques, such as Perturb and Observe (P&O) and Incremental Conductance (INC), have been developed to optimize energy extraction from the PV array (Reza 2020), (Chen 1999). Recent studies have also focused on improving the efficiency of PVPS by utilizing advanced control techniques, including Space Vector Modulation (SVM) and Modified Space Vector Modulation (MSVM), to enhance the operation of the induction motor (IM) drives and minimize inrush currents (Niravadya 2018), (Angadi 2021).

While single-stage PVPS are commonly used due to their simplicity and lower cost, double-stage topologies incorporating DC-DC boost converters have been found to offer better control over the DC link voltage, thus improving system performance (Singh 2018). However, DC motors in PVPS suffer from high maintenance due to brushes and commutators, which has led to the adoption of induction motors and permanent magnet synchronous motors (PMSMs) for better efficiency and reduced maintenance (Murshid 2020),(Khan 2019). The use of PMSMs in solar PV-based water pumping systems offers several advantages, including higher power factor, better efficiency, and high torque-to-weight ratio, making them ideal for PVPS applications (Mudlapur 2019), (Ibrahim 2019). Additionally, the integration of intelligent control strategies, such as artificial neural networks and fuzzy logic controllers, has further optimized the performance of PVPS, especially under partial shading conditions (Shukla 2019), (Tarczewski 2016). Furthermore, advancements in power converter technologies and the development of more efficient algorithms for MPPT have enhanced the overall reliability and cost-effectiveness of solar water pumping systems (Kalla 2020). Kalla et al. (Wiki 2022) designed a solar-powered water pumping system with a PV array, DC-DC boost converter, IMD, and centrifugal pump. The system uses Modified Space Vector PWM (MSVPWM) to reduce inrush current, sensor count, and harmonics, improving efficiency and reducing costs. MATLAB/Simulink simulations showed satisfactory results.

3. Methods

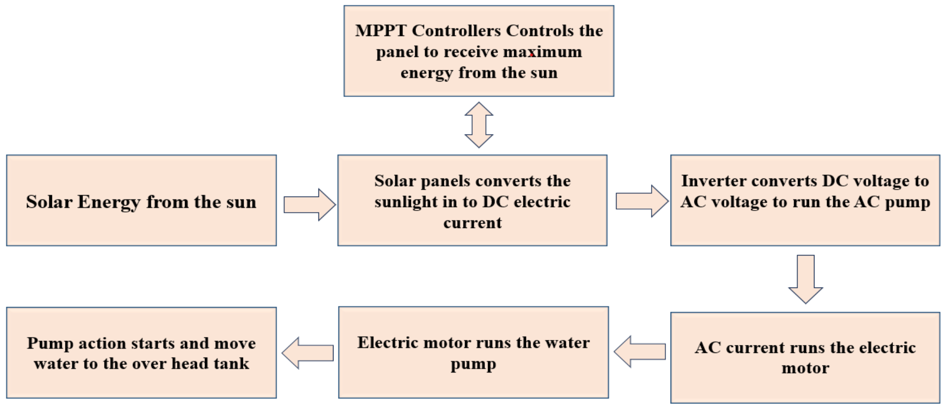

Figure 1. Block Model of Solar Water Pumping System

A solar-powered water pumping system consists of several photovoltaic (PV) panels. **Figure 1** shows the basic block diagram of the solar water pumping system. The core components of these panels are solar cells, which convert light into electricity. These panels, commonly referred to as photovoltaics, derive their name from the Greek words "phos" (light) and "volta" (electricity) (online 2022). Each solar cell consists of two or more specially prepared layers of semiconducting material, typically silicon. When exposed to sunlight, these layers generate direct current (DC) electricity. The wiring within the panel collects this DC power, which is then directed to an inverter that converts it into alternating current (AC) to power an AC pump.

The pump is activated whenever sunlight is available, and any excess water can be stored in an overhead tank for later use. In summary, the solar-powered water pump operates using electricity generated by photovoltaic panels, which harness sunlight to power the system. The water supplied by the pump can be used for various purposes, including irrigation, watering livestock, or providing potable drinking water (Horne 2001). **Figure 2** below illustrates an equivalent water pumping system.

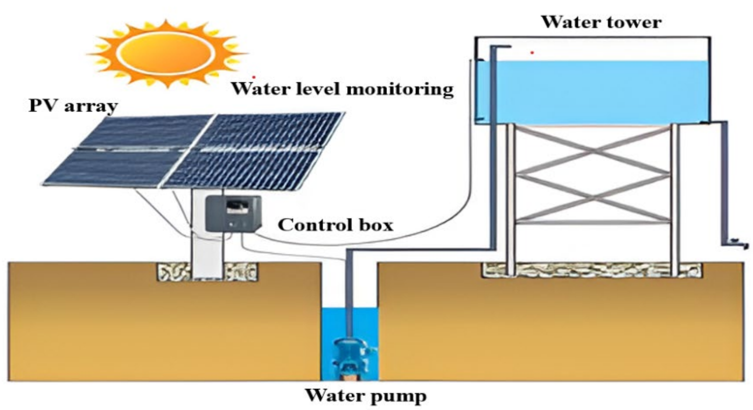

Figure 2. Solar Water Pumping System

3.1 Modelling of PV Cell

The use of equivalent electric circuits allows for modeling the characteristics of a PV cell. This method is implemented in MATLAB programs for simulations. The same modeling technique is applicable for simulating a PV module. Figure 3 and 4 shows ideal single diode model and Equivalent model of single diode solar cell with series and shunt resistance respectively.

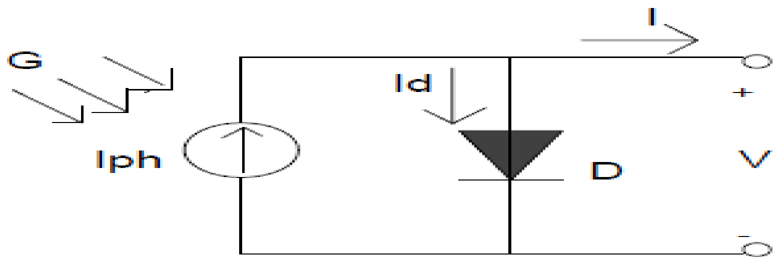

Figure 3. Ideal Single Diode Model

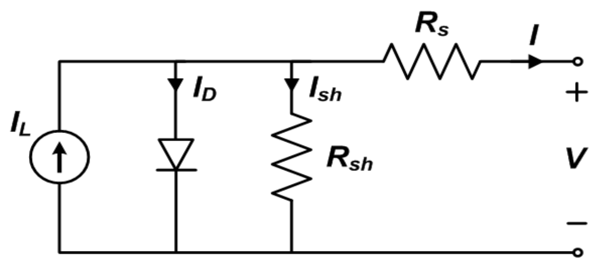

Figure 4. Equivalent model of single diode solar cell with series and shunt resistance.

Then the output voltage and current relations comes out to be (Meunier 2020), (Subudhi 2019)

$$I = I_{ph} - I_d$$

$$I_d = I_s[\exp\left(\frac{V}{nV_{th}}\right) - 1$$

$$V_{th} = \frac{k.T}{q}$$

$$I = I_{ph} - I_d = I_{ph} - I_s[\exp\left(\frac{V}{nV_{th}}\right) - 1$$

$$I = I_{ph} - I_s\left[\exp\left(\frac{(V + R_S)}{nV_{th}}\right) - 1\right] - \frac{V + R_s I}{R_{sh}}$$

$$I = I_{ph} - I_s\left[\exp\left(\frac{(V+R_S)}{nV_{th}}\right) - 1\right] - G_{sh}(V + R_S I)$$

The output power is given by:

$$P_{pv} = I_{pv} * V_{pv}$$

The short-circuit current (I_c) become:

$$I_{sc} = I_{ph} - I_s\left[\exp\left(\frac{(q.R_{sh}.I_{sc})}{n.K.T}\right) - 1\right]$$

The current photo (I_h) for all operating conditions is related to the current photo at reference conditions by,

$$I_{ph}(T)=\frac{G}{G_{ref}}[I_{ph-ref}+\mu I_{sc}(T - T_{ref})]$$

$$G_{ref} = 1000\frac{W}{m^2} and\ T_{ref} = 298.15K$$

The open circuit voltage (V_{oc})

$$V_{oc}(T) = \frac{nkT}{q}\log[1 + \frac{I_{ph}}{I_s(T)}]$$

3.2 Boost Converter

The power for the boost converter can come from any of the solar panels in the system. The process of changing one DC voltage to another is called DC-to-DC conversion (Rodrigues 2011). A boost converter is a type of DC-to-DC converter that increases the output voltage above the input voltage. It is sometimes referred to as a "step-up converter" because it "steps up" the source voltage.Since power (P = V × I) must be conserved, the output current will be lower than the input current. This relationship ensures that the overall power remains constant, but the voltage is increased at the cost of a decreased current. **Figure 5** below illustrates the basic circuit of a boost converter.

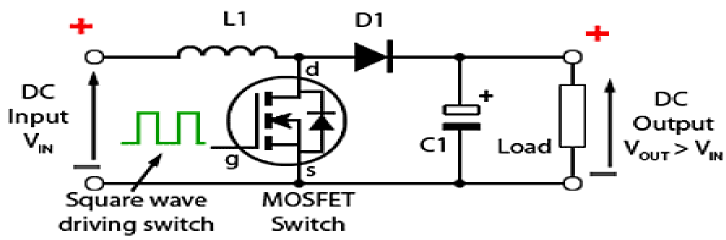

Figure 5. Boost Converter Circuit

A solar-powered water pumping system consists of several photovoltaic (PV) panels, and the core components of these panels are solar cells. The power generated by the solar cells is often regulated using a step-up boost converter. Linear Technology manufactures a wide range of high-performance boost switching regulator ICs and boost switching controller ICs, featuring both synchronous and non-synchronous switches. These regulators are capable of handling input voltages from less than 2V up to over 100V, with switching frequencies up to 4 MHz and efficiencies reaching as high as 96% (Tamrakar 2015). Additionally, these regulators can operate in Burst Mode, enabling very low quiescent currents in the tens of microamps. This feature, combined with high efficiency, allows for compact, low-profile boost converter circuit designs with minimal external components. Other features of these step-up switch-mode voltage regulators include micropower operation, adjustable or synchronizable switching frequencies, small package sizes, and flexibility in design. Many of these ICs can also be configured as SEPIC regulators or flyback topology switching regulators, making them versatile solutions for a range of applications.

3.3 Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) is an algorithm used in charge controllers to extract the maximum available power from a photovoltaic (PV) module under varying environmental conditions. The voltage at which a PV module produces maximum power is referred to as the *maximum power point* (MPP) or *peak power voltage*. This point varies depending on factors such as solar radiation, ambient temperature, and the temperature of the solar cells themselves (Hasaneen 2008). For example, a typical PV module operates at a maximum power voltage of around 17 V when the cell temperature is 25°C. However, this value can drop to around 15 V on a very hot day and may rise to 18 V under colder conditions.

3.4 Permanent Magnet DC Motor

In a DC motor, the armature rotates within a magnetic field. The basic working principle of a DC motor relies on the fact that when a current-carrying conductor is placed within a magnetic field, it experiences a mechanical force. **Figure 6** shows the internal construction of a Permanent Magnet DC Motor (PMDC).

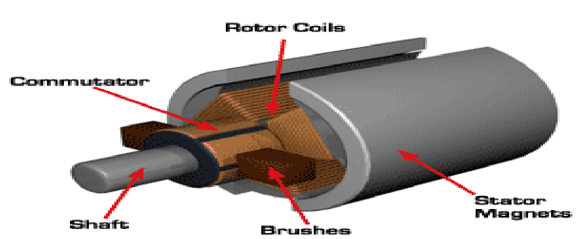

Figure 6. PMDC Motor

All types of DC motors operate based on this principle, where the key component is the establishment of a magnetic field.This magnetic field can be created using different types of magnets—either electromagnets or permanent magnets. When a permanent magnet is used to generate the magnetic field in a DC motor, the motor is called a Permanent Magnet DC Motor (PMDC). If you have ever opened a battery-operated toy, you've likely found a small motor inside it. This motor is typically a PMDC motor. PMDC motors are simple in construction and widely used in applications such as automobile starter motors, windshield wipers, washers, blowers for heaters and air conditioners, and in various toys (Wiki 2022). Because the magnetic field strength in a PMDC motor is fixed and cannot be externally controlled, field control is not possible. As a result, PMDC motors are used in applications where precise speed control is not required. These motors are typically small, with fractional or sub-fractional kilowatt ratings.

3.5 Centrifugal Pumps
Centrifugal pumps are the most commonly used kinetic-energy pumps. The centrifugal force generated by the impeller pushes the liquid outward from the center (the "eye" of the impeller) into the pump casing. The differential head can be increased by speeding up the impeller, using a larger impeller, or adding more impellers. The impeller and the fluid being pumped are sealed from the outside by packing or mechanical seals. Shaft radial and thrust bearings control the movement of the shaft, minimizing friction during rotation (Online 2022)

3.6 System Design in Matlab Simulink

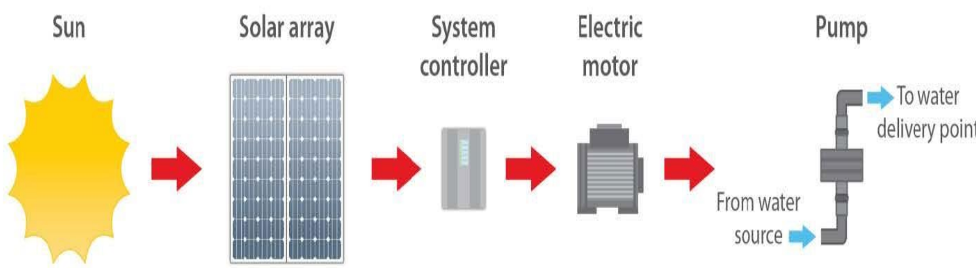

Figure 7. An electric water pump as part of a solar pumping system

Figure 7 shows a basic diagram of an electric pump as part of a solar pumping system. In this system, the water pump is powered by a photovoltaic (PV) array. The system consists of three main components: the pump, its controller, and the PV array. With these three elements, the system remains relatively inexpensive and low-maintenance. The system is designed to operate when there is sufficient sunlight and water available for pumping. To improve system performance, it is advisable to either include water storage or "oversize" the PV array, allowing the system to pump water even under low light conditions.

3.6.1 Boost Converter Design
The MATLAB Simulink model of the DC-DC Boost Converter is shown in **Figure 8**. A DC-DC boost converter is designed to step up the input voltage to a higher output voltage. This is why it is also referred to as a *step-up converter*. In this system, a PWM (Pulse Width Modulation) generator is used to control the duty cycle, which acts as the input. The input voltage is provided by the PV module, and it is stepped up through the combination of components such as the IGBT (Insulated-Gate Bipolar Transistor), inductor, capacitor, resistor, and diode, arranged as shown in **Figure 5**. **Figure 8** illustrates the complete DC-DC Boost Converter model in MATLAB Simulink.

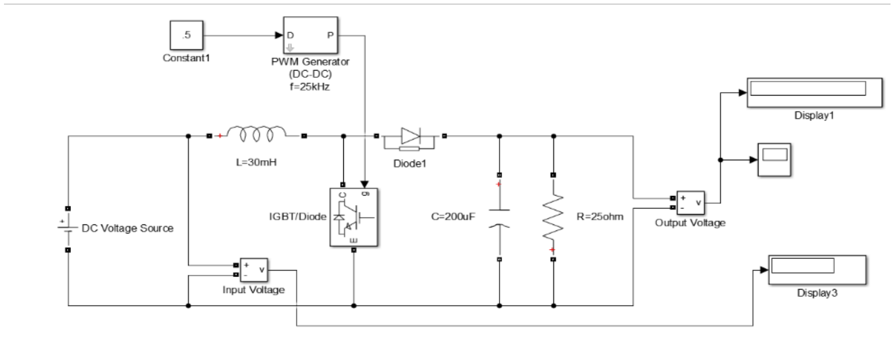

Figure 8. DC-DC Boost converter model in MATLAB Simulink

3.6.2 Directly Couple Solar Pumping System Model

Figure 9 shows the directly coupled solar pumping system. This system integrates a photovoltaic (PV) module, a Permanent Magnet DC (PMDC) motor, and a centrifugal pump. Power from the PV module is used to drive the motor, which in turn provides torque to the pump. To observe the system's performance, we can monitor the flow rate of the pump and the motor speed using the Scope block in MATLAB Simulink.

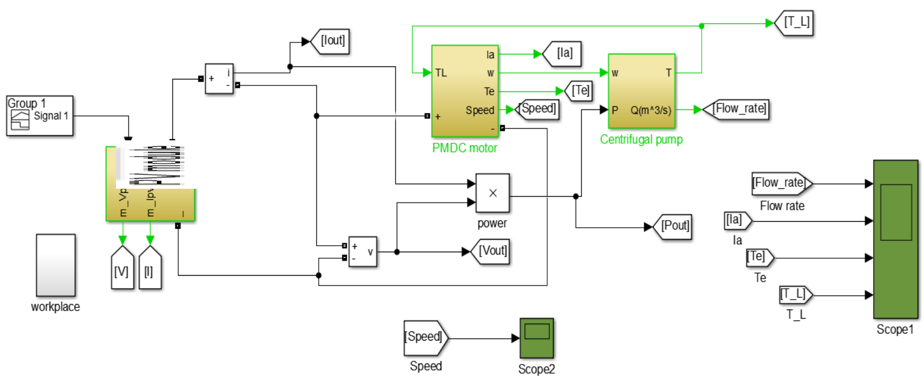

Figure 9. Directly Coupled solar pumping system.

3.6.3 Overall System Design

Figure 10 shows the MATLAB Simulink model of a solar water pumping system, which includes the MPPT (Maximum Power Point Tracking), boost converter, battery, speed controller, PMDC motor, and centrifugal pump. In this system, the MPPT tracks the maximum power, which is obtained by multiplying the voltage and current from the PV module. The output voltage from the PV modules is then stepped up by the boost converter. The boosted output current is fed into the PMDC motor, which drives the centrifugal pump. To control the motor speed, a speed controller subsystem is used. Finally, the flow rate of the pump and the speed of the motor can be monitored using the Scope block in MATLAB Simulink.

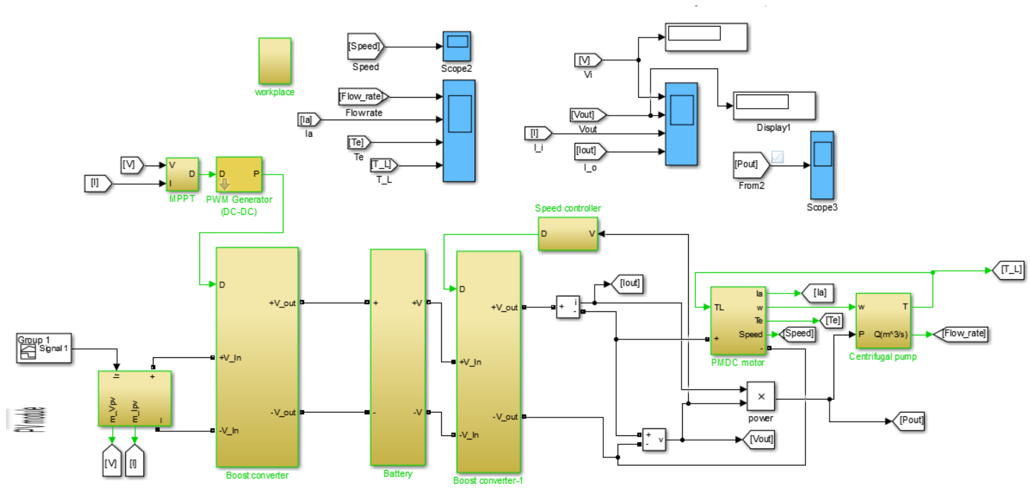

Figure 10. Solar pumping system with MPPT, Boost converter and battery storage system.

4. Results and Discussion

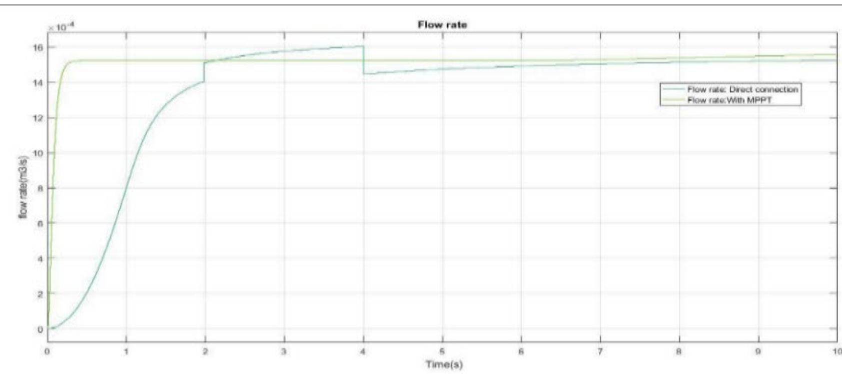

Figure 11. Comparison of Flow Rate

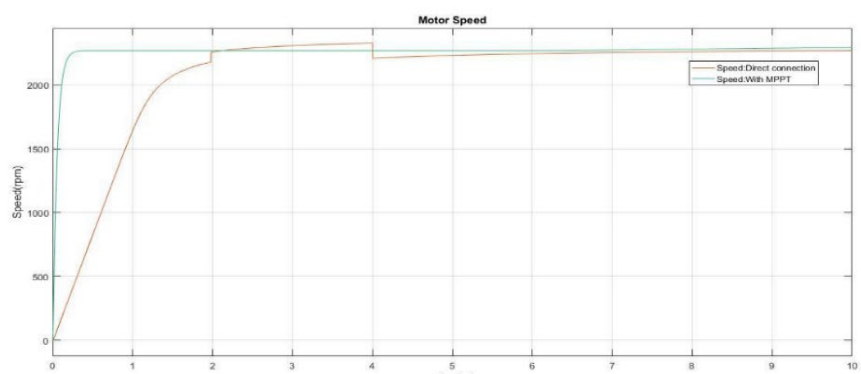

Figure 12. Comparison of Motor Speed

comparison of **Figures 11** and **12** demonstrates that the solar pumping system equipped with Maximum Power Point Tracking (MPPT), a boost converter, and battery storage outperforms the directly coupled system. The MPPT optimizes the solar panels' operating point to maximize power output, thereby enhancing system efficiency, especially under varying sunlight conditions. The boost converter plays a critical role by stepping up the voltage from the solar panel to meet the pump's requirements, ensuring consistent operation even under low solar input. In contrast, the directly coupled system depends solely on real-time solar output, which makes it more susceptible to inefficiencies or failure during periods of low sunlight. Additionally, the MPPT and battery storage system offers the advantage of storing excess energy generated during peak sunlight hours. This stored energy can then be used during periods of low sunlight, thus improving the system's reliability and minimizing downtime. In conclusion, the integration of MPPT, a boost converter, and battery storage significantly improves energy efficiency and provides a more reliable water pumping solution, particularly in regions with unpredictable sunlight.

5. Conclusion

The performance of solar water pumping systems depends significantly on their design. In this analysis, we compared two systems: a directly coupled solar water pumping system with Maximum Power Point Tracking (MPPT) and a system that includes both MPPT and battery storage. Both systems were modeled and simulated using MATLAB/Simulink. In the directly coupled system, the rotor speed, flow rate, and armature current are directly proportional to solar irradiation. As solar irradiation fluctuates, these parameters also change, affecting the performance of the Permanent Magnet DC (PMDC) motor. The efficiency of the PMDC motor depends on its rotor speed, with peak efficiency achieved at a specific speed determined by its characteristic curves. Moreover, the water demand often limits the input power to the rated capacity of the PMDC motor, which may require selecting a motor with a higher horsepower (HP) rating. This increase in HP raises both capital costs and the need for a larger water storage tank to accommodate the extra power generated, further escalating the system’s costs. In contrast, a solar water pumping system equipped with battery storage and a regulating boost converter offers superior efficiency. This system allows the motor to operate at a more consistent speed, improving its efficiency and enabling it to function closer to its optimal performance point. The battery storage stores excess energy, providing a buffer during cloudy days and enhancing the system’s reliability. Consequently, a motor with a lower horsepower rating can be selected, which reduces the initial capital investment and allows for a smaller water storage tank, compared to the directly coupled system. While integrating battery storage and a boost converter may increase initial capital costs, the enhanced efficiency and reliability of the system ultimately outweigh the benefits of the directly coupled approach. Operating at a consistent speed led to higher motor efficiency, lower horsepower requirements, and reduced storage tank size, making the system more cost-effective and efficient overall.

Future work will focus on further optimizing the system's design, particularly the integration of IoT-based monitoring for real-time performance tracking and predictive maintenance. This will enable better monitoring of system health and improve long-term reliability, ensuring that the system remains a viable solution for irrigation and other applications in rural areas.

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