

PMSM Drive-Based Single-Stage Autonomous Solar Water Pumping System with Adaptive Filter Controller

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Abstract

In this project, a single-stage freestanding solar photovoltaic (SPV) array-fed water pumping system is powered by a Permanent Magnet Synchronous Motor (PMSM). One of the main accomplishments of the work is the creation of a novel Modified Vector Control (MVC) that improves the torque responsiveness of the system. (2) The development of a novel single-stage Variable Step-Size Incremental Conductance (VSS-INC) technique that provides rapid Maximum Power Point Tracking (MPPT) without the need for an intermediate-stage DC-DC converter. (3) The addition of an SPV Power Feed-Forward Term (FFT), which accelerates the system's overall response in dynamic scenarios. The system consists of an SPV array, a PMSM, a pump load, and a three-phase Voltage Source Inverter (VSI). The SPV array converts solar energy into electrical energy, while the VSI acts as a Power Processing Unit (PPU) to supply the necessary currents to power the

PMSM. The associated pump pumps water while the PMSM revolves. This system is modeled and simulated using MATLAB/Simulink with the Simscape Electrical toolkit, and its performance under different climatic conditions is verified in a lab prototype.

Keywords: Power Processing Unit (PPU), Maximum Power Point Tracking, SPV Power Feed-Forward Term, MATLAB/Simulink, VSS-INC

1. Introduction:

With its clean operation, low maintenance requirements, and less reliance on grid electricity, solar water pumping is an efficient renewable energy alternative for remote locations. Nevertheless, issues including power losses, DC-link voltage fluctuations, slow transient response, and ineffective motor operation plague traditional SPV pumping systems. Because of their high efficiency, high power density, low torque ripple, small size, and quick

dynamic response, PMSM drives are favored over traditional induction motors for solar water pumping applications. Torque ripples, slow response, and higher control complexity are some of the drawbacks of traditional PMSM control methods including DTC, V/f control, and standard vector control[1]. To enhance torque regulation and dynamic response, the suggested Modified Vector Control (MVC) adds an extra torque control loop and an SPV power feed-forward term. The suggested system uses a single-stage Variable Step-Size Incremental Conductance (VSS-INC) MPPT approach for maximal solar-power extraction. It improves system efficiency, lowers size and cost, and supports dependable solar-powered water pumping by doing away with the intermediate DC–DC converter and offering faster and more precise MPP tracking[2].

2. Existing System:

A PV array, a DC-DC converter for MPPT and DC-link control, an inverter, and an induction motor or PMSM to power the water pump are the usual components of conventional standalone solar water pumping systems. The MPP is tracked by standard P&O and fixed-step INC techniques under temperature and irradiance changes, but the extra converter adds switching devices, control complexity, and

conversion losses[3]. Additionally, during abrupt changes in the amount of PV power available, these systems may show delayed dynamic response, increased PMSM speed, and torque variations.

2.1. Disadvantages :

1. The number of components and system complexity increase with the need for additional DC-DC converters.
2. Additional switching and conduction losses are caused by many power-conversion stages.
3. In situations where irradiance changes quickly, conventional MPPT algorithms could track more slowly.
4. By creating oscillations around the maximum power point, fixed-step MPPT techniques can lower energy consumption.
5. Unwanted variations in PMSM speed and torque may result from abrupt changes in solar power.
6. Conventional control approaches' limited dynamic responsiveness can lower pumping performance in situations where the environment is changing quickly.

3. Proposed System:

A Permanent Magnet Synchronous Motor (PMSM) and an improved adaptive control mechanism are used in the proposed single-stage standalone SPV-fed water pumping system. A three-phase Voltage Source

Inverter (VSI) is directly supplied by the SPV array, doing away with the need for an intermediary DC–DC converter. By dynamically modifying its step size based on the operating conditions, a Variable Step-Size Incremental Conductance (VSS-INC) MPPT algorithm continually monitors the maximum available solar power[4]. An SPV Power Feed-Forward Term (FFT) offers quick correction for fluctuations in available PV power, while a Modified Vector Control (MVC) approach controls the PMSM currents, torque, and speed. The control signals' stability and quality are further enhanced by the adaptive filter controller. The VSI produces the necessary three-phase currents for the PMSM and serves as the primary power-processing unit. Because the PMSM is mechanically connected to a centrifugal water pump, solar energy can be directly transformed into hydraulic energy.

3.1. Block Diagram:

The adaptation process iteratively updates the filter coefficients in response to changing conditions, while the filtering process uses the current filter coefficients to generate the output and error signals[5]. This procedure improves the overall filtering performance by minimizing the error and optimizing the chosen cost function.

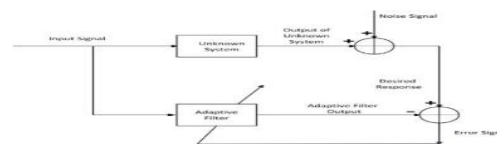


Fig. 1. Adaptive Filter Controller

In order to reduce the discrepancy between the desired and filtered signals, the suggested Adaptive Filter Control continuously modifies its filter coefficients using the error signal[6].

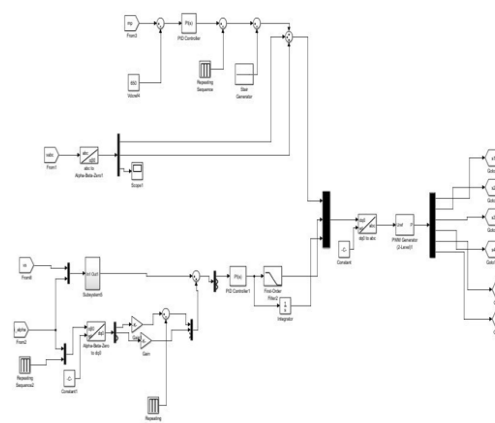


Fig. Proposed control circuit (with Adaptive Filter Controller)

Fig.2. block diagram of proposed system

3.2. Working Process

Under different operating situations, this adaptive approach improves accuracy, lowers filtering error, and boosts overall dynamic performance. While the VSS-INC MPPT collects the full power that is available and serves the three-phase VSI directly in the single-stage configuration, the SPV array produces DC power. With MVC controlling speed and torque[7], SPV feed-forward enhancing transient response, and the adaptive filter lowering control-signal

fluctuations, the VSI powers the PMSM. In order to power the water pump effectively and consistently in a variety of solar situations, the PMSM transforms electrical energy into mechanical energy.

3.2. Advantages:

1. The number of power-processing components is decreased by single-stage power conversion.
2. There is no need for an intermediary DC-DC converter, which lowers conversion losses, system size, and cost.
3. Under changing irradiance, VSS-INC MPPT offers quicker tracking of the maximum power point[8].
4. Steady-state oscillations around the maximum power point are lessened by a variable step size.
5. Better PMSM torque and speed control is offered by Modified Vector Control.
6. The dynamic sensitivity to abrupt variations in solar power is enhanced by the SPV Power Feed-Forward Term.
7. Coordinated control and adaptive filtering enhance the standalone pumping system's overall performance and stability.

4. Project Objective:

This project's primary goal is to use a PV array and PMSM drive to create an effective single-stage autonomous solar water pumping system. Using a Variable Step-Size

Incremental Conductance (VSS-INC) MPPT technique, the system seeks to extract the maximum amount of solar power possible; enhanced PMSM speed and torque regulation are provided by the Modified Vector Control (MVC) with torque control loop[9]. To improve overall pumping efficiency, dependability, and performance under changing solar irradiance and temperature conditions, an SPV power feed-forward term is included to speed up the dynamic response during variations in solar power.

5. Problem Statement:

PV power, DC-link voltage, PMSM speed, torque, and pumping output all fluctuate as a result of temperature and solar irradiation. While fixed-step MPPT requires a trade-off between tracking speed and steady-state oscillations, conventional systems require additional DC–DC conversion[10]. In order to accomplish effective single-stage operation, quick reaction, and steady PMSM performance, the suggested system makes use of VSS-INC MPPT, Modified Vector Control, SPV Power Feed-Forward control, and adaptive filtering.

6. Literature Survey:

6.1. Using an induction motor and a five-phase impedance-source inverter, Hassan et al. (2024) studied MPPT control for a solar

PV water pumping system. Through appropriate inverter design and MPPT control, the study sought to increase PV power utilization under a variety of operating situations. The suggested solution maintained enough water-pumping capability while efficiently harnessing solar energy[11]. For dependable autonomous solar water-pumping systems, the paper emphasizes the significance of suitable inverter and MPPT approaches.

6.2. For a solar-powered water pump, Shetty and Sabhahit (2024) suggested a hybrid MPPT method that combines Gray Wolf Optimization (GWO) and Incremental Conductance (INC). While INC enhances tracking close to the maximum power point under varying irradiation, GWO offers global-search capacity. When compared to traditional methods, the suggested methodology showed better MPPT tracking properties. The work demonstrates that hybrid MPPT methods can strike a balance between steady-state performance and global tracking capacity[12].

6.3. For standalone solar PV water-pumping systems, Abbassi and Saidi (2024) introduced an MPPT method based on the Chaotic Horse Herd Optimizer (CHHO). Under various photovoltaic working conditions, the suggested approach

effectively determines the maximum power point.

The outcomes showed how metaheuristic optimization might enhance PV power extraction and pumping efficiency. For real-world applications, however, its computational complexity drives the creation of quicker and easier MPPT methods.

7. Implementation methodology: The SWP system configuration is displayed in the figure. A water pump, a PMSM, a three-phase voltage source inverter (VSI), and an SPV array make up this system (from left to right). To prevent any reverse current from entering the SPV array, a diode (D) is placed between the SPV array and the VSI. A suitable number of parallel and series combinations of SPV modules make up the SPV array[13]. Electrical energy is produced as the photons hit the SPV array's surface. The DC connection of VSI receives this produced electrical energy. The power processing unit is the VSI. It transforms this electrical energy into rotational mechanical energy by rotating the PMSM with a pump attached to it.

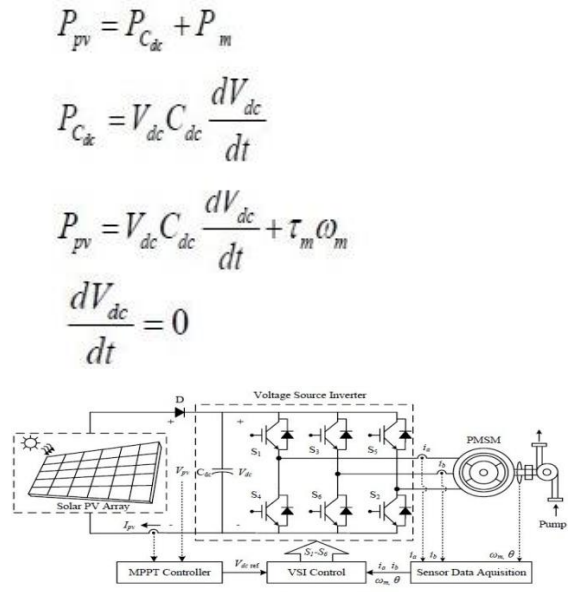


Fig.3. Configuration diagram of SWP system

$$P_{pv} = 0 + \tau_m \omega_m$$

For a pump type load, the torque is considered as,

$$\tau_m \propto \omega_m^2$$

Let K_m be pump proportional constant. Since

$$\tau_m = K_m \omega_m^2$$

Therefore, (5) becomes,

$$P_{pv} = K_m \omega_m^3$$

The relationship shows that the cube of motor speed (ω_m) is proportional to the SPV array power (P_{pv}). Faster reaction to variations in solar power is made possible by the SPV power feed-forward (FFT), which immediately generates the second speed reference ω_{ref2} from the available PV power. The speed controller generates the reference electromagnetic torque $T_{e,ref}$ by comparing the generated ω_{ref} with the PMSM speed ω_m [14]. The torque controller generates the reference quadrature-axis current $i_{q,ref}$ by processing the torque error

that is determined by comparing $T_{e,ref}$ and $T_{e,est}$. PMSM speed and torque response are therefore improved by the suggested MVC with torque control loop and SPV-FFT.

8.Solar Energy PVSystem:While a photovoltaic (PV) system uses a solar PV array, a solar inverter, and related electrical components to convert sunlight into electrical energy, the suggested system uses the PV array as the main source for water pumping and can use solar tracking to enhance energy generation[15].

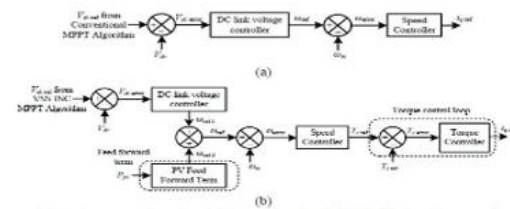


Fig.4. Conventional and modified vector control

In low-irradiance situations, an optional battery storage device saves extra energy and acts as a backup. To effectively run the water pump, the MPPT-controlled VSI and PMSM drive process the PV electricity[16]. The system offers a dependable, low-maintenance, silent, and clean alternative for remote water pumping and agricultural irrigation.

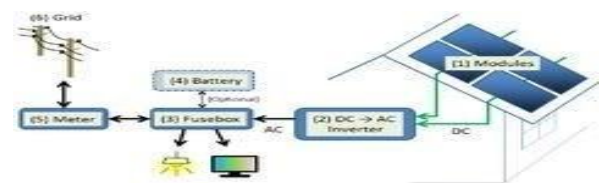


Fig.5. Diagram of a Standard Home Photovoltaic System

The SPV array supplies the DC link and three-phase VSI by using parallel strings to boost current and power and series-connected modules to acquire the necessary DC voltage. PV power extraction and PMSM operation are controlled by the VSS-INC MPPT, MVC, SPV power feed-forward term, and adaptive filter based on solar energy availability[17]. For effective agricultural and remote water delivery, the PMSM transforms electrical energy into mechanical energy and powers the water pump.

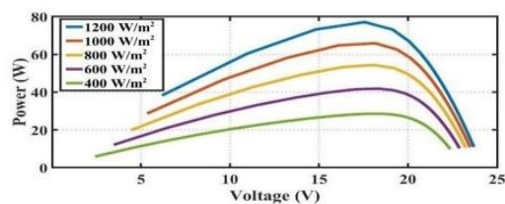


Fig.6.A PV array's performance varies depending on the amount of sunlight.

With a maximum power of 66 Wp at 17.6 V under 1000 W/m², the PV array operates at irradiance levels of 400–1200 W/m² at 25°C. MPPT continuously modifies the electrical operating point to extract the most available PV power, much like mechanical solar tracking. The Fractional Open-Circuit Voltage technique estimates the MPP by using the roughly constant ratio between the

maximum-power voltage VMPP and the open-circuit voltage VOC.

$$V_{MPP} \approx k_1 V_{OC}$$

$$I_{MPP} \approx k_2 I_{SC}$$

8.1. Fractional Short-Circuit Current:

While solar energy offers clean, sustainable, and low-maintenance power, the Fractional Short-Circuit Current approach assumes a near-linear relationship between ISC and IMPP, with k_2 generally between 0.78 and 0.92. PV systems do, however, have many drawbacks, such a high initial cost, a wide installation area, unavailability at night, and decreased power generation in overcast situations.

8.2. MPPT:

By modifying the PV operating point in response to shifting voltage, current, and irradiance circumstances, the MPPT regulator continuously monitors the MPP and enhances solar energy use and conversion efficiency[18].

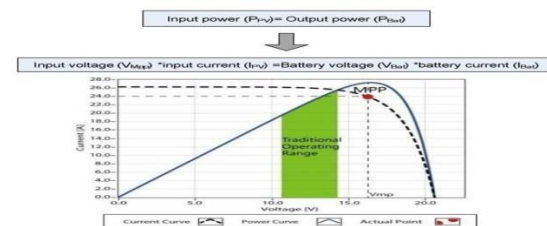


Fig.7. Maximum Power Point Curve

The PV power curve may have several local maximum power points when partially shaded by trees, clouds, snow, or other

obstacles. An MPPT controller can change the operating point to make better use of the available PV power, in contrast to a traditional PWM regulator. The PV array typically has a single Global Maximum Power Point (GMPP) where the maximum power is obtained, notwithstanding the possibility of several local MPPs.

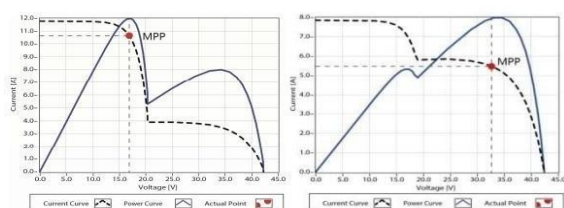


Fig. 8. Curves with several MPP points

While P&O periodically modifies PV voltage and monitors power variations to approach the MPP, advanced MPPT techniques track multiple MPPs under partial shading, with variable step-size P&O minimizing oscillations. By comparing instantaneous conductance I/V with incremental conductance $\Delta I/\Delta V$, the Incremental Conductance (INC) approach determines the MPP using the zero-slope condition of the PV power-voltage curve. When opposed to traditional controllers running close to battery voltage[19], the MPPT controller continuously modifies the PV reference voltage and optimizes the operating point through power-electronic conversion.

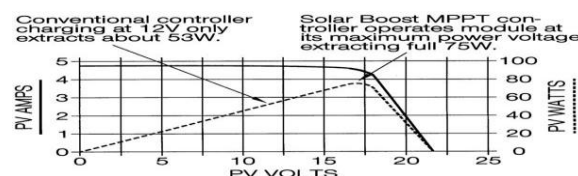


Fig.9. V-I Characteristics

Regardless of battery voltage, the MPPT system determines the maximum-power voltage of the PV module and runs it at roughly 17 V to harvest all 75 W of available power. The PV output is then transformed into the necessary battery charging voltage using a high-efficiency DC-DC converter. Compared to a traditional charge controller, this can provide more useful charging energy by increasing the charging current by about 1.85 A, or 42%.

8.3.Battery Energy Storage System (BESS):

By storing electrical energy and offering quick power support during peak demand, emergencies, and frequency-control requirements, a battery energy storage system (BESS) enhances grid stability. Compact and quicker to install than big pumped-storage systems, BESS units are ideal for short-duration energy delivery and can be placed close to power plants, loads, or client locations. The viability of BESS for grid support, backup power, and renewable energy applications has increased due to

declining battery costs and growing renewable energy integration[20].

8.4.Construction:

Although they are typically larger and intended for grid-scale energy storage and power control, battery storage power plants are comparable to UPS systems. Bidirectional converters and inverters are necessary for charging and grid connection because batteries store energy as DC whereas power grids primarily use AC. Lead-acid, nickel-cadmium, sodium-sulfur, and lithium-ion batteries are among the several battery technologies that are chosen according to factors like cost, efficiency, safety, longevity, and application needs. While flow batteries and lead-acid batteries are still appropriate for longer-duration and smaller storage applications, lithium-ion batteries have become commonly used in utility-scale storage due to their decreasing cost.

8.5.Market Development and Deployment:

The adoption of battery energy storage devices has increased dramatically as renewable-energy output has expanded and the requirement for flexible grid resources has grown[18]. The growing usage of BESS in utility-scale, commercial, industrial, and residential applications has been facilitated

by advancements in battery technology, power electronics, battery-management systems, thermal management, and safety systems.

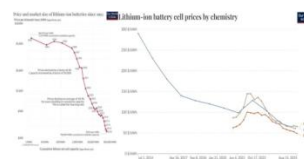
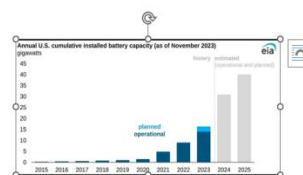


Fig. Lithium-ion battery cell prices by chemistry, 2014-2025 and Growth in installed battery capacity in the U.S. between 2015 and 2023



Reliable Solar Water Pumping (SWP) operation is ensured by appropriate subsystem design, and global BESS capacity is developing as a result of growing renewable energy integration and decreasing battery costs. The SPV array and DC-link capacitor of the suggested system's 7.8 kW PMSM are made to enable dependable and effective functioning[19].

8.6.Design of SPV Array:

The SPV array is designed using the solar-cell modeling approach, which transforms photon energy into electrical energy. To offset power-conversion losses, an SPV array rated at about 8.4 kW under STC (1000 W/m² 25°C) is chosen for the 7.8 kW PMSM. To achieve the necessary voltage, current, and power ratings, the array uses

KC200GT PV modules coupled in series and parallel.

$$P_{pv} = P_{mpp} = 8.4 \text{ kW}$$

$$n = \frac{P_{mpp}}{P_{mp}} = \frac{8400}{200.143} \approx 42$$

$$n_s = \frac{V_{mpp}}{V_{mp}} = \frac{500}{26.3} \approx 21 \text{ modules}$$

$$n_p = \frac{P_{mpp}}{n_s * V_{mp} * I_{mp}} = \frac{8400}{21 * 26.3 * 7.61} \approx 2 \text{ modules}$$

$$C_{dc} = \frac{I_0}{2 * \omega_e * \Delta V_{dc}} = \frac{8400 / 560}{2 * 314.16 * 0.02 * 560} = 2132 \mu F$$

The suggested control uses three PI controllers to combine Modified Vector Control (MVC) for PMSM speed and torque management with VSS-INC MPPT for maximal SPV power extraction. While the integrated control technique improves dynamic performance under changing solar circumstances, the SPV-FFT offers feed-forward action to improve transient response[20]. The VSS-INC method employs a smaller step size during steady-state operation to minimize oscillations and a higher step size during transient situations for quicker MPP tracking. As a result, it offers a balance between enhanced tracking precision, quick dynamic reaction, and lower power losses near the MPP.

$$V_{dc \text{ ref}}(k) = V_{dc \text{ ref}}(k-1) \pm \text{Step}$$

$$\text{Step} = K_{vs} * |dP_{pv} / dV_{pv}|$$

where dP_{pv} and dV_{pv} are the differences in SPV array power and voltage at the k th and $k-1$ th sampling instant, respectively, and K_{vs} is the step size constant. Fig. displays the additional equations used in the VSS-

INC algorithm. The MPPT performance is significantly impacted by the choice of K_{vs} . A greater step size is the basis for determining k_{vs} . For quick dynamic response, step max is first chosen.

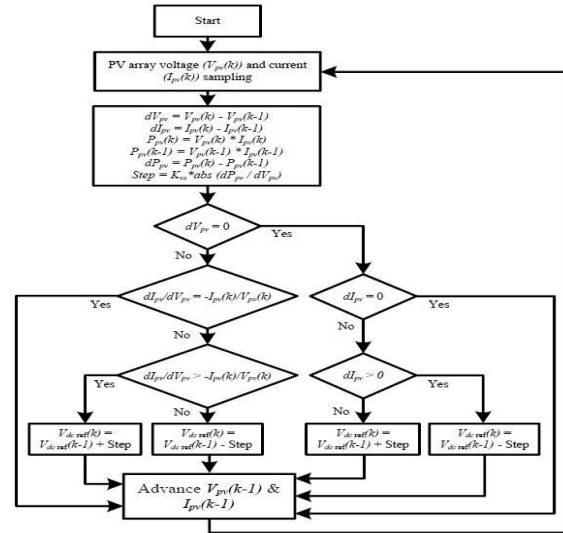


Fig.10. Single stage VSS-INC algorithm

$$K_{vs} * |dP_{pv} / dV_{pv}|_{\text{Constant Step} = \text{Step}_{\max}} < \text{Step}_{\max}$$

$$K_{vs} < \text{Step}_{\max} / |dP_{pv} / dV_{pv}|_{\text{Constant Step} = \text{Step}_{\max}}$$

$$V_{\alpha} = \frac{1}{3} (2V_a - V_b - V_c) \quad V_{\beta} = \frac{\sqrt{3}}{3} (V_b - V_c)$$

$$i_{\alpha} = \frac{1}{3} (2i_a - i_b - i_c) \quad i_{\beta} = \frac{\sqrt{3}}{3} (i_b - i_c)$$

$$\psi_{\alpha} = \int (V_{\alpha} - R_s i_{\alpha}) dt + \psi_{\alpha 0}$$

$$\psi_{\beta} = \int (V_{\beta} - R_s i_{\beta}) dt + \psi_{\beta 0}$$

$$T_{e \text{ est}} = \frac{3}{2} p (\psi_{\alpha} i_{\beta} - \psi_{\beta} i_{\alpha})$$

$$V_{dc \text{ error}}(k) = V_{dc \text{ ref}}(\hat{k}) - V_{dc}(k)$$

This error is fed to the DC link PI voltage controller. The DC link voltage controller reduces the error and its output is considered as ω_{ref1} is estimated as,

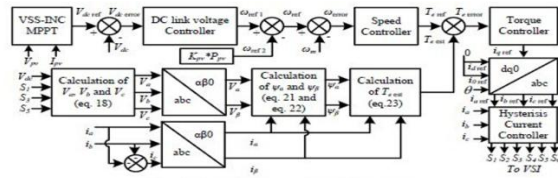


Fig.11. DC link PI voltage controller

9.Results and discussions:

Modified Vector Control (MVC) Simulation Circuit Diagram

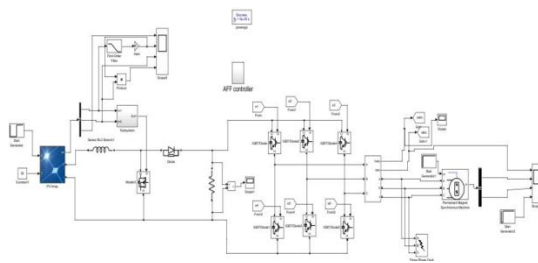


Fig.12. simulation model

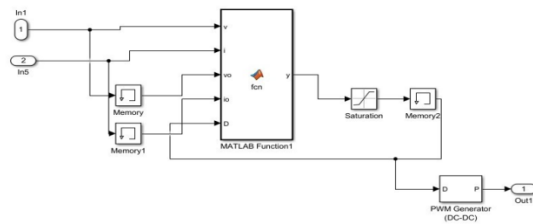


Fig.13. Simulation model INC MPPT method

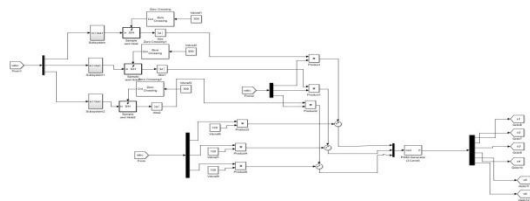


Fig.14. Simulation model AFF control method

9.1.Starting and Steady-State Performances:

The system's initial and steady-state

performance at solar irradiances of 1000 W/m² and 500 W/m², respectively, with a constant temperature of 25 °C, are depicted in the figures. The SPV array parameters' fluctuation is depicted in the images. It is evident that the reference DC-link voltage Vref produced by the VSS-INC algorithm is successfully followed by the SPV array voltage Vpv. The parameters of the SPV array show extremely quick convergence. The SPV array parameters settle in less than 0.01 seconds in both scenarios. With the motor achieving its steady-state speed from zero in 0.04 seconds and the stator currents closely following their reference values, the suggested MVC control offers a quick PMSM response.

9.2.Dynamic Performance with Changing

Insolation: At 25 °C, the system is tested for variations in irradiance between 1000 and 500 W/m² and 500 and 1000 W/m², with only slight variations in Vpv and notable variations in Ipv, SPV power, PMSM speed, torque, and load power. The system achieves a new steady state in 0.03 seconds[19], with motor parameters rising or falling in response to changes in irradiance, while the MPPT keeps the PV operating voltage close to the MPP. Ipv marginally increases while Vpv and Ppv fall with temperature changes from 25 °C to 50 °C and back, resulting in

equivalent decreases in PMSM speed, torque, and load power.

Simulation Results

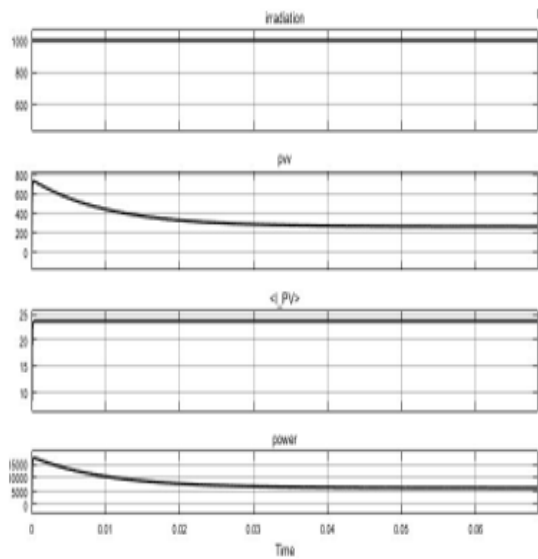


Fig.15.Starting and steady state performance for (a-b) insolation of 1000W/m²

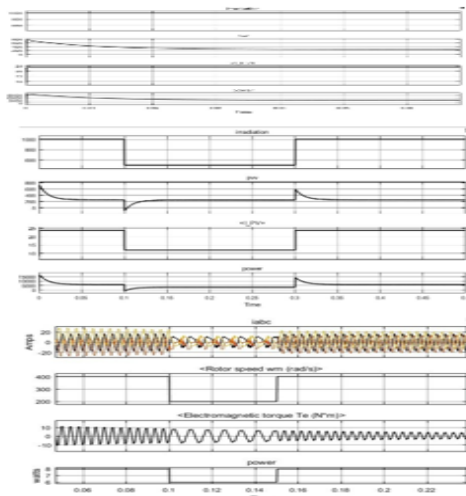


Fig.16.Dynamic performance during insolation change(a)from1000W/m²to500 W/m² and (b) from 500 W/m² to 1000 W/m²

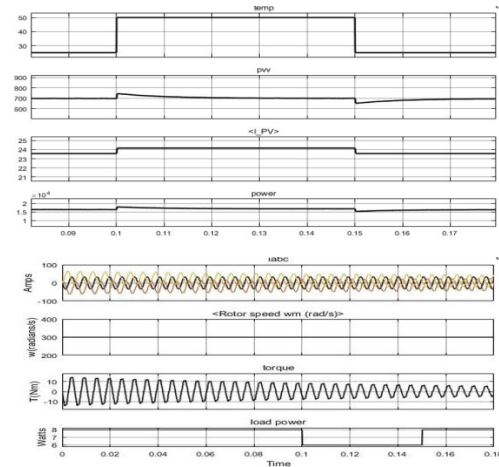


Fig.17. Dynamic performance during temperature change(a)from 25°C to 50°C and(b)from 50°C to 25 °C

To continuously enhance filtering effectiveness, an adaptive filter makes use of changeable parameters that are modified by an optimization algorithm. It uses feedback via an error signal for parameter adaptation and is helpful for systems where operational conditions or signals change over time. The adaptation algorithm is guided toward better performance by a cost function, typically the Mean Square Error (MSE), which assesses the error[20]. Adaptive filters are widely utilized in communication, imaging, and medical monitoring applications because to the development of digital processors.

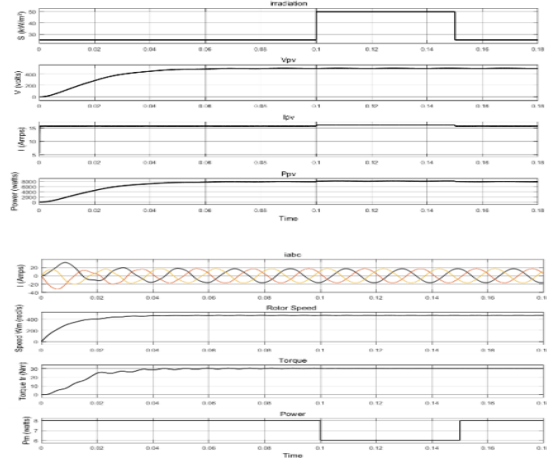


Fig.18. Dynamic performance during insolation changes: (a) from 1000 W/m² to 500 W/m² and (b) from 500 W/m² to 1000 W/m².

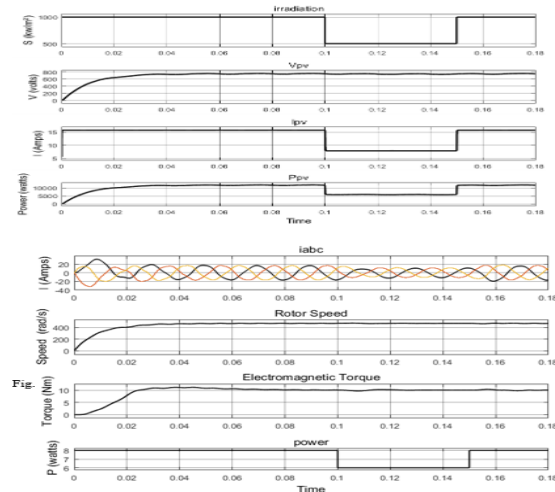


Fig.19. Dynamic performance during temperature changes: (a) from 25 °C to 50 °C and (b) from 50 °C to 25 °C.

Fig.19. Dynamic Performance under Varying Temperature

At constant irradiance of 1000 W/m², the system is assessed for temperature changes from 25 °C to 50 °C and 50 °C to 25 °C, where a rise in temperature marginally increases I_{pv} but dramatically decreases V_{pv} and P_{pv} . As a result, PMSM speed, load torque, and load power all drop and

stabilize in 0.03 seconds. The SPV voltage, power, PMSM speed, load torque, and load power all rise when the temperature drops back to 25 °C, exhibiting stable dynamic performance.

10. Advantages:

- High solar energy utilization: Power extraction is improved and conversion losses are decreased with single-stage conversion using rapid VSS-INC MPPT.
- Better motor performance: When irradiance changes, MVC and adaptive filtering offer quicker PMSM speed and torque response with fewer oscillations.
- Economical and efficient operation: The system is appropriate for solar-powered agricultural pumping due to its cheap operating costs, dependable off-grid operation, and simplified hardware.

11. Applications:

- Applications in agriculture and irrigation: reservoirs, farm ponds, greenhouses, drip irrigation, and agricultural fields.
- Borewells, rural dwellings, livestock, rainwater collection, and community water systems are examples of domestic and communal water supplies.
- Remote and specialized applications: appropriate small-scale industrial water circulation, small water treatment facilities, and remote-area pumping.

12.Conclusion:

In MATLAB simulation and hardware validation, the suggested SPV-fed SWP system with VSS-INC MPPT and MVC-based PMSM control performs satisfactorily. When compared to traditional INC, VSS-INC increases MPPT tracking accuracy and speed while reducing steady-state oscillations. With faster dynamic performance, the MVC and feed-forward control enhance PMSM speed and torque responsiveness. By doing away with the intermediate DC-DC converter, the single-stage topology lowers component costs, losses, and system complexity. Overall, the efficiency and practical appropriateness of the suggested system for solar water pumping applications are validated by the good match between modeling and experimental findings.

13.Future scope:

The suggested single-stage autonomous SWP system's future scope encompasses expanded MPPT approaches, AI-assisted control, IoT-based remote monitoring, and enhanced PMSM control for increased efficiency. Operational dependability and maintenance can be enhanced by real-time monitoring of solar power, water level, flow rate, motor speed, and system condition. AI-based forecasting can optimize pump

performance depending on water demand, weather, and solar irradiation. Dry running, water waste, and needless energy use can all be decreased with the use of water-level detection, predictive maintenance, and intelligent energy management. The system can be expanded to provide a dependable, affordable, small, and eco-friendly solution for smart agriculture, irrigation, livestock, and rural water delivery.

14.References:

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