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Design and Performance Evaluation of Fuzzy Logic Controlled PMSM Based Solar Pump Drive

Nabisa Shaik, M.Tech (PE&D),
Dr. R. Suja Mani Malar, Associate Professor,
Department of Electrical and Electronics Engineering, National Institute of Technical Teachers Training and Research (NITTTR), Chennai

***Abstract* – This paper presents single-stage SWPS using PMSM drive is proposed in this paper, which is based on fuzzy logic control (FLC). Proposed system based on a photovoltaic array is directly connected to the PMSM by a single stage power conversion system, which reduces a number of power converters, power loss, and power system complexity. The FLC is programmed to control the motor speed and enhance system performance in the different solar irradiance conditions. The FLC is able to deal with the nonlinear operating characteristics and the variations of the parameters and shows stable operation and good dynamic response unlike conventional controllers. The controller provides better speed tracking accuracy, reduces settling time, and ensures smooth water pumping operation in the presence of irradiance fluctuations. The results from the simulation show the superior motor speed regulation, utilization of available solar power and reliability of system operation. The proposed solution is simple, efficient, and cost-effective for standalone applications of solar water pumping, especially in remote and agricultural areas where a reliable water supply is crucial.**

Key words – Solar Photovoltaic system, VSS-INC MPPT, PMSM, Fuzzy Logic Controller.

1. INTRODUCTION

Solar PV powered water pumping has proven to be a viable option to provide water in areas of agriculture and remote areas where conventional electric power is not available. They can use the solar energy as a renewable source of energy, which helps minimize the use of fossil fuels and offers a sustainable and environmentally friendly irrigation and water management solution. Advancements in power electronic converter and photovoltaic (PV) technology have added to the feasibility and efficiency of such systems [1] [2]. The recent developments have been directed to enhance performance of SWPS under various environmental conditions. PV-fed pumping systems have become highly reliable and efficient due to the advanced motor control techniques, the improved configurations of the converter and the efficient energy management strategies [3, 4]. Furthermore, Permanent Magnet Synchronous Motor (PMSM) has gained much attention due to its compact design, excellent dynamic performance, low maintenance and high efficiency [5] [6]. As for PV applications, PMSMs offer high torque density, high power factor and high energy efficiency, which makes them well suited to PV water pumping applications, compared with conventional induction motors [7]–[8]. Several control methods have been devised to control the speed and torque of motors, and these methods can be used to take advantage of these benefits. Of these, vector control and direct torque control methods are most commonly used as they allow for independent control of torque and flux, thus improving the dynamic performance. But they could suffer from torque ripple, parameter sensitivity and poor performance in rapidly changing operating conditions [9] [10]. Another significant difficulty with solar powered pumping systems is regulating the operation of motor when there is abrupt change in solar radiation and load demand. These changes affect the amount of PV power available and can decrease pumping system efficiency [11]. MPPT techniques have then been widely used to maximize the energy extracted from PV arrays. Despite the extensive literature on MPPT which has been developed to enhance MPPT tracking speed and efficiency, the impact of PV voltage, current and motor torque fluctuations on the overall dynamic performance of

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the system still exists [12-13]. To overcome these limitations, intelligent control techniques are becoming more and more popular in applications of renewable energies. The methods above, in particular, Fuzzy Logic Control (FLC), have been shown to be effective with handling the nonlinear system characteristics and parameter uncertainty without the need for an accurate mathematical model of the system. Compared with many conventional control strategies, fuzzy controllers offer better control accuracy, robustness and transient response [14, 15]. Very recently, AI has even been integrated into solar water pumping systems to enhance predictive energy management and optimize the entire system operation, showcasing the pivotal role of intelligent control techniques in renewable energy systems [16]. Encouraged by these developments, this paper introduces a Modified Vector Control (MVC) combined with FLC technique for SWPS based on single stage PMSM. The proposed controller is the conventional torque controller that is replaced to improve the dynamic performance, system stability, settling time and minimize the voltage and current fluctuation, under varying environmental conditions.

II. System Description

The solar PV array produces the DC power and the MPP is obtained with help of MPPT controller. The generated power is fed to the voltage source inverter (VSI) transforms the available DC power into a balanced three-phase AC supply required to operate the PMSM. proposed control system is a Fuzzy Logic based VSI which adjusts motor speed and torque according to the feedback signals from the sensors. The PMSM drives the water pump, which can realize efficient water pumping operation, with better dynamic response, reduction of torque settling time and stable PV power use.

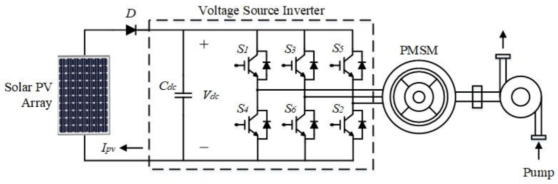

Fig.1. Proposed Solar PV Fed PMSM Water Pumping System

Fig 1 shows proposed system consists of stage (SS) PV water pumping system. Using PMSM drive and Modified Vector Control (MVC) strategy based on Fuzzy Logic Controller (FLC). The designed system can pump water efficiently, have better dynamic response and stable operation under varying solar irradiance condition.

A. Solar Photovoltaic (PV) Array

PV array is the main source of energy and the electricity generation is achieved by the PV array using the solar radiation. The PV voltage and current produced dependent on variations in the ambient solar irradiation and temperature. A VSS-INC MPPT technique is used to obtain maximum utilization of the available solar energy

B. the proposed VSS-INC MPPT algorithm MPPT

The VSS-INC MPPT algorithm uses a continuous tracking process to change the operating voltage of the PV array in order to determine the maximum power operating point. The variable step size mechanism not only increases the tracking speed, but also decreases steady-state oscillations, which in turn improves power extraction efficiency.

C. VSI

Three phase Voltage Source Inverter is the power processing unit of the system. It transforms the direct current generated by the PV array into regulated three-phase alternating current which is necessary to drive the PMSM. Combined with the Modified Vector Control and the proposed Fuzzy Logic Controller, the inverter switching signals are generated.

D. Fuzzy Logic-Based Modified Vector Control

The conventional torque controller is replaced by FLC to enhance The dynamic performance of the PMSM drive is achieved. Speed error information is provided to the fuzzy controller to produce control actions to adjust the motor torque. The MVC technique improves the existing control system and helps to achieve smooth speed control, which also minimizes the torque settling time and oscillations.

E. Permanent Magnet Synchronous Motor

The PMSM is a type of machine that converts electrical energy provided by the inverter into mechanical energy. The PMSM has the

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characteristics of high efficiency, rapid response and high power density, which is appropriate to solar water pumping application? Motor speed is controlled based on solar electricity generation and pumping needs.

F. Water Pump

The PMSM shaft is mechanically connected with centrifugal water pump. Is used to pump water into fields for irrigation, for watering animals, and for domestic consumption. The motor speed determines the pumping performance, and the proposed FLC-MVC strategy is an effective control of the motor speed.

G. Overall System Operation

The PV array generates electric power which is fed into the VSS-INC MPPT algorithm to work under MPPT conditions. The power generated is fed to the VSI which is feeding to the PMSM via the proposed Modified Vector Control method using Fuzzy Logic. The PMSM is used in the water pump to run it at a constant speed with low torque ripple and high dynamics. The proposed control strategy also minimizes PV voltage and current fluctuations, resulting in enhanced efficiency and reliable system operation.

Table 1. System Parameters

Parameter	Value
PV Power	8.4 kW
DC-Link Voltage	570 V
Motor Type	PMSM
Rated Speed	300 rad/s
Rated Torque	25 N·m
Controller	FLC-MVC
MPPT Method	VSS-INC
Inverter	Three-Phase VSI
Load	Water Pump

III. Control Topology

In order to regulate the PMSM drive, proposed controller consists of three parts, which are a VSS-INC MPPT algorithm, MVC and a Fuzzy Logic Controller (FLC). The VSS-INC algorithm has been developed to maximize the PV array output, and MVC controls the stator currents and the motor torque. The FLC is used to replace traditional torque controller, and to calculate the reference torque signal according to the speed error, which can make the response speed faster and reduce the torque oscillations. The control signals generated is then passed through the current regulator to generate inverter switching pulses for the operation of PMSM.

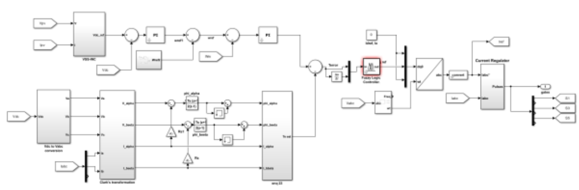

Fig.2.Proposed Fuzzy Logic-Based Modified Vector Control (FLC-MVC) Configuration of the PMSM-Based Solar Pumping System

Speed Error Calculation

Fig 2 shows speed control loop operates to continuously check difference between the desired speed and actual PMSM rotor speed. This is error signal that shows the difference between the operation of the motor and the desired operation. This is what the controller's goal is: to get the motor to run at the desired speed and reduce this error

$$e\omega = \omega ref - \omega m \qquad (1)$$

Where:

- $e\omega$ = speed error
- ωref = reference speed
- ωm = actual motor speed

The higher the speed error, the further off the operating point. The generated corrective control action is based primarily on this signal as the input to the FLC.

Change in Speed Error

Speed error change can give information about the dynamic behavior of motor. It shows if the error is getting bigger or smaller over time and allows the controller to predict the behaviour of the system.

$$\Delta e\omega = e\omega(k) - e\omega(k-1) \qquad (2)$$

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Where:

- $\Delta e\omega$ = change in speed error
- k = current sampling instant
- $k-1$ = previous sampling instant

The fuzzy controller adopts speed error and variation as the control variables, which can obtain smooth control action without overshoot and transient performance, while the control action is reduced.

Fuzzy Logic Torque Reference Generation

The input variables are then passed through the Fuzzification, inference rules and Defuzzification processes of the FLC to produce reference value of electromagnetic torque.

$$Te* = F(e\omega, \Delta e\omega) \quad (3)$$

Where:

- $Te*$ = reference electromagnetic torque (N·m)
- $F(\cdot)$ = fuzzy inference function

The torque reference is generated which indicates the torque needed to be applied to the PMSM to operate it to the desired state. The fuzzy controller doesn't require that the process be exactly modelled and is able to deal with the nonlinearity.

PMSM Electromagnetic Torque Equation

The Te is generated from the interaction between the currents in the stators and the permanent magnet flux in the rotors. Torque used to power the pump load.

$$Te = \frac{3}{2}\frac{p}{2}[\lambda f iq + (Ld - Lq) id iq] \quad (4)$$

Where:

- Te = electromagnetic torque (N·m)
- P= number of poles
- λf = permanent magnet flux linkage
- id– Current in direct axis
- iq– Quadrature-axis of the stator current (A).
- Ld– Inductance in d axis circuit.
- Lq– The inductance of the circuit in the q-axis.

The q-axis current directly contributes to torque production as shown in this equation. Thus correct regulation of iq is crucial for obtaining accurate torque control.

Clarke Transformation

Three-phase currents are measured and converted to two orthogonal stationary reference frame components. This change decreases the complexity of the system, and makes vector control easier to implement.

$$i_\alpha = \frac{2}{3}\left(i_a - \frac{i_b}{2} - \frac{i_c}{2}\right)$$

$$i_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2} i_b - \frac{\sqrt{3}}{2} i_c\right) \quad (5)$$

Where:

- ia, ib, ic = three-phase stator currents
- $i\alpha, i\beta$ = currents measured in the stationary reference frame.

The currents are transformed to be used in flux estimation and torque estimation in the MVC structure.

Stator Flux Estimation

The signals of the stator voltage and current are used to obtain the stator flux components. For correct operation of vector control, it is necessary to estimate the flux accurately.

$$\psi\alpha = \int (V\alpha - Rsi\alpha)dt$$

$$\psi\beta = \int (V\beta - Rsi\beta)dt \quad (6)$$

Where:

- $\psi\alpha, \psi\beta$= stator flux components
- $V\alpha, V\beta$ = stator voltage components
- Rs = stator resistance

The estimated flux components are used for torque estimation and are the magnetic state of the PMSM

Stator Flux Magnitude

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Magnitude of the total stator flux is formed by the orthogonal flux components.

$$\varphi_s = \sqrt{\varphi_\alpha^2 + \varphi_\beta^2} \tag{7}$$

Where:

- ψs = resultant stator flux linkage

The magnitude of a stator flux controls the strength of rotor magnetic field, which in turn directly affects the capability for torque production of a machine.

Electromagnetic Torque Estimation

The stator flux vector and current vector are used to approximate the actual motor torque.

$$Te = \frac{3}{2}\frac{p}{2}(\psi\alpha i\beta - \psi\beta i\alpha) \tag{8}$$

Where:

- $\psi\alpha, \psi\beta$= stator flux components
- $i\alpha, i\beta$ = stator current components

The torque estimation error is obtained by comparing the estimated torque with the reference torque reference torque generated by the fuzzy control used to find the required control action.

Current Regulation

The current regulator keeps the difference between the reference current and the actual current to a minimum. Generates voltage commands needed for inverter switching in the controller.

$$v_d^* = k_p(i_d^* - i_d) + k_i \int (i_d^* - i_d)dt$$

$$v_q^* = k_p\left(i_q^* - i_q\right) + k_i \int \left(i_q^* - i_q\right)dt \tag{9}$$

Where:

- v_d^* v_q^*= reference voltage components
- Kp = proportional gain
- Ki = integral gain
- $id *$ = reference currents
- id = measured currents

These equations provide good steady-state performance and accurate current tracking.

Inverter Output Voltage Generation

The VSI is used to convert direct current voltage received from the PV array into controlled three phase Alternating Current (AC) voltage.

$$Vabc = f(S1, S2, S3, S4, S5, S6)Vdc \tag{10}$$

Where:

- $Vabc$= inverter output voltage
- Vdc = DC-link voltage
- $S1 - S6S\_1 - S\_6S1 - S6$ = inverter switching states

This switching pulse is what the controller is able to produce to control the magnitude and frequency of the inverter output voltage fed into the PMSM.

Mechanical Dynamics of PMSM

The mechanical dynamics equation is the motor speed response.

$$j\frac{dw_m}{dt} = Te - TL - B\omega m \tag{11}$$

Where:

- J = moment of inertia
- Te = electromagnetic torque
- TL = load torque
- B = viscous friction coefficient
- ωm = rotor speed

This equation indicates that the motor will accelerate if the developed electromagnetic torque is larger than the torque demanded of the load.

IV. Proposed Method

A single-stage solar driven PMSM based water pumping system is proposed to implement Fuzzy Logic Controller (FLC)-based Modified Vector Control (MVC) strategy for to enhance the efficiency of the system. The main goal of the proposed approach to enhance dynamic response of motor

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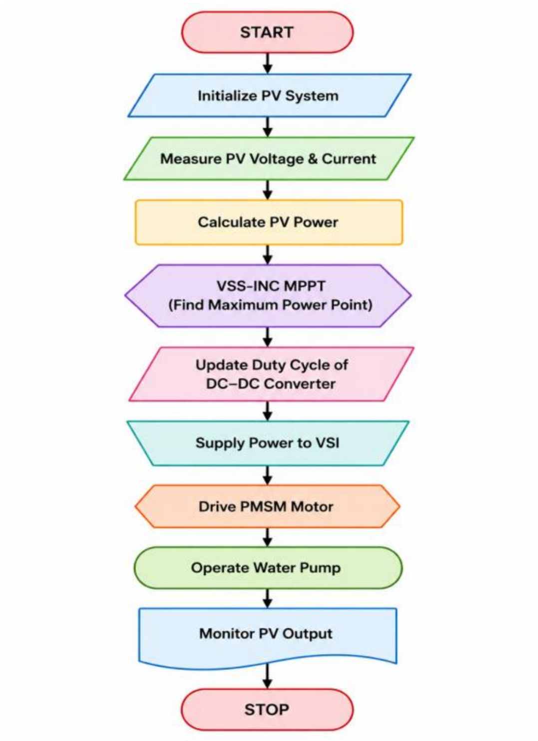
drive, decrease the torque settling time and minimize voltage and current fluctuations of the photovoltaic system when in different operating conditions. The system is made up of Solar PV Array, VSS-INC MPPT algorithm, VSI, PMSM drive, and a centrifugal water pump. The PV array changes the energy of the sun into electrical energy and is only source of energy for the pumping system. The amount of solar power that is available fluctuates as the irradiance varies, so an efficient MPPT technique must be used to get them to generate the maximum power from the PV array. Array. For this purpose the following VSS-INC MPPT algorithm is used. The variable step-size mechanism adaptively varies the duty ratio for the specific operating condition, which results in faster convergence to the maximum power point and simultaneously less steady-state oscillation of the duty ratio, unlike conventional MPPT techniques. This results in increased efficiency and efficient use of solar energy in the PV system.

The power extracted from the DC power source is directly fed to the VSI, The inverter transforms the DC output into a balanced three-phase AC supply required for PMSM operation. The gate pulses applied to the inverter are generated using the proposed control strategy FLC-based Modified Vector Control. The conventional MVC method relies on a common torque controller to regulate the torque. The controller performance deteriorates when the irradiance and load changes quickly, however, with a deteriorated performance settling time increases and the response is oscillatory. In order to address these issues, a Fuzzy Logic Controller is integrated in the torque control loop. The proposed fuzzy logic controller receives two input signals, and four output variables, namely, the control signal. The controller can produce an appropriate control signal according to the predetermined linguistic rules. The controller does not need to have a complete mathematical model of the PMSM and is effective even when the characteristics and parameters are nonlinear and uncertain. This means that the motor drive has quicker motor response and enhanced motor control accuracy. The Modified Vector Control is implemented to control the stator currents in the d-q reference frame order to achieve d-q decoupling. FLC could be used in conjunction with the MVC, which enhances the existing motor regulation and will give smooth operation of the motor under both transient and steady state conditions.

Proposed controller effective in suppressing torque oscillations and improving the stability of the system. In addition, proposed control method mitigates the voltage and current fluctuations in PV due to sudden load variations. The enhanced power management feature ensures a stable operation and continuous water pumping performance of the system in spite of the changing environmental conditions. The PMSM has a higher speed tracking ability and lower electromagnetic disturbances, which results in better efficiency and reliability. Hence, the proposed FLC-MVC approach is able to enhance torque control, dynamic performance, power quality and stability of the whole system, making it an efficient and robust control solution for the single-stage solar water pumping (SWP) systems.



Flowchart 1. Proposed VSS-INC MPPT-Based PMSM Solar Water Pumping System.

Flowchart 1 shows working sequence of the proposed VSS-INC based SWPS. At beginning, the PV system is initialized, followed by the continuous measurement of PV voltage and current, which are used to calculate PV power generation. The operating point is calculated by VSS-INC MPPT algorithm. of maximum power and dynamically adjusts the switching ratio of the DC–DC power converter to harvest the maximum energy available from PV

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array. Extracted power is fed to VSI which controls the PMSM. Finally, PMSM is responsible for the operation of the water pump and the PV output is monitored continuously ensuring that the system performs reliably, efficiently and with stable operation under various solar irradiance conditions.

V. Simulation Results & Discussion

FLC

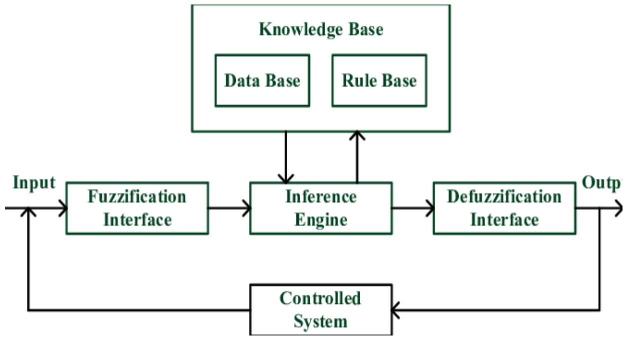

Fig.3. Fuzzy logic controller

The fig 3 shows FLC is applied to enhance the performance of SWPS with the PMSM. It is not based on an exact mathematical model but is instead based on human thinking and decision-making principles. This property makes the controller suitable for nonlinear systems in which operating conditions are constantly changing because of fluctuations in the solar radiation and load demand. The controller gets input signals like torque error, and the change of torque error. The inputs are fuzzified by using predefined membership functions, and the result is linguistic variables.

The set of control rules stored in the rule base is then evaluated by fuzzy inference mechanism to find the desired control action. The fuzzy output obtained is then converted to crisp control signal using the Defuzzification process and applied to the motor control system. The FLC continually modifies the control signal based on system conditions, resulting in more rapid torque control, smoother speed response and system stability.

It can effectively suppress torque oscillations, shorten settling time and improve the tracking performance of PMSM. Proposed SWPS uses FLC in place of the torque controller, which allows the effective utilization of the available PV power under different environmental conditions. This results in better dynamic properties of the motor, lower fluctuations and better overall pumping performance.

A. Starting and Steady State Performances

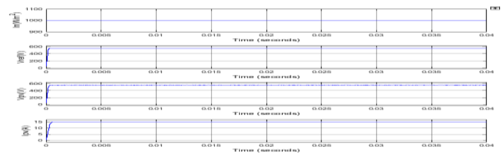

Fig.4. PV System Performance under Constant Solar Irradiance

The figure 4 shows the operation of proposed SWPS based on a FLC with a constant solar irradiance of 1000 W/m². The voltage from (Vpv) is closely followed by the reference voltage ($Vref$) with a very small deviation. The PV current (Ipv) is maintained around 15 A, which shows that MPPT operation is stable and very efficient in extracting power from the PV array. Results show stable operation of PV, the accuracy of effectiveness of voltage stabilization and the overall system behavior during steady operating conditions

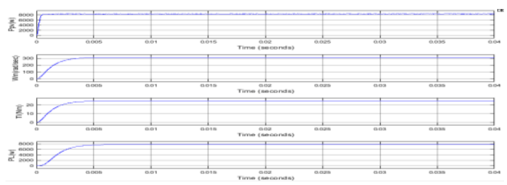

Fig.5. Dynamic Performance of the Proposed FLC-Based PMSM Water Pumping System

Fig 5 shows dynamic response of the proposed Fuzzy Logic Controller (PMSM water pumping system). When the motor is operated, the speed is reached in a short time with minimal over speed, and at around 300 rad/s the motors rated speed. The electromagnetic torque is regulated to around 25 N·m to guarantee smooth motor operation. The steady state output power of the PV array is rapidly achieved at around 8 kW and the steady state mechanical power is also attained at about 8 kW, showing a good power transfer and improved dynamic performance. The results show that the system is fast responding, stable operating and solar energy efficient under steady state condition.

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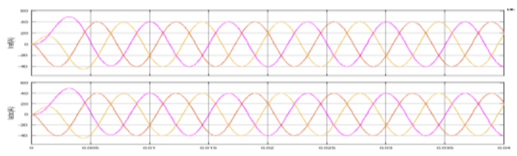

Fig.6. Three-Phase Stator Current Tracking Performance of PMSM

Fig 6 show the three-phase reference currents ($Iref$) and measured three-phase currents of stator ($Iabc$) of the PMSM under the proposed Fuzzy Logic Controller are illustrated in the figure. The actual currents are very close to the reference currents and have a balanced sinusoidal wave form, with a 120° phase difference. This indicates the current regulation accuracy, low current distortion and successful performance of the Modified Vector Control based on FLC.

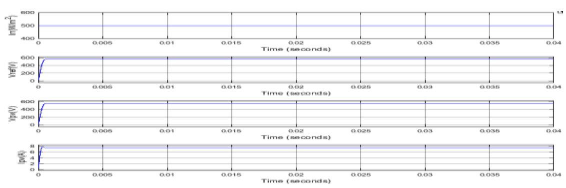

Fig.7. Steady-State PV Characteristics under Constant Irradiance

Fig 7 shows response of PV system for fixed irradiance of 500 W/m². The ($Vref$) and PV output voltage (Vpv) are almost constant around 570 V, which demonstrate the accuracy of MPPT operation. The PV current (Ipv) reaches steady levels around 6 A, indicating the steady generation and regulation of voltage. The findings show stable PV operation and energy extraction efficiency with the proposed system that is based on the Fuzzy Logic Controller.

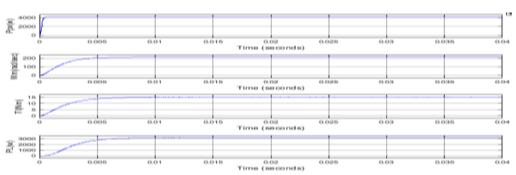

Fig.8. Dynamic Response of PMSM Water Pumping System at Reduced Solar Irradiance

The fig 8 shows dynamic performance of the proposed Fuzzy Logic Controller (FLC) based PMSM water pumping system under reduced solar irradiance condition. Steady state value of the motor speed is around 200 rad/s and the electromagnetic torque is around 15 N·m when the motor speed reaches steady state. Steady values of PV output power and mechanical power are approximately 4 kW, suggesting efficient power conversion and stable motor performance. Under lower solar power availability, the results illustrate the capability of the proposed controller to ensure reliable performance, fast response, and efficient energy utilization.

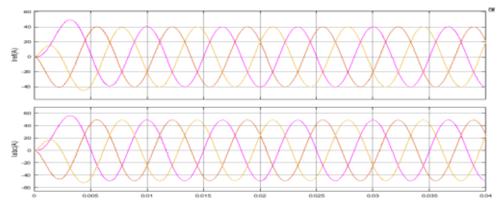

Fig.9. Reference and Actual Three-Phase Stator Current Waveforms at Reduced Irradiance

The fig 9 shows reference current ($Iref$) and actual stator current ($Iabc$) of PMSM for reduced solar irradiance under the proposed Fuzzy Logic Controller are shown. The actual currents correctly follow the reference currents in a balanced sinusoidal fashion, and with the correct 120° phase displacement. The robust PMSM drive, with the effective tracking performance, confirms the good performance of the current control, low current distortion and stability of the proposed Modified Vector Control strategy with FLC.

B.Performance Evaluation under Changing Solar Irradiance

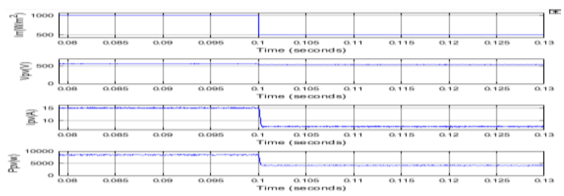

Fig.10.PV System Response under Sudden Irradiance Change (1000 W/m² to 500 W/m²)

figure 10 shows dynamic response of the proposed Fuzzy Logic Controller based solar water pumping system, when the solar irradiance level reduced from 1000 W/m² to 500 W/m² at 0.1 s. PV current falls from around 15 amps to 6 amps, as the irradiance decreases; and the PV power falls from around 8 kW to 4 kW as the irradiance decreases. The PV voltage is maintained almost constant at 570 V which indicates stability of the voltage regulation and good

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MPPT operation. The outcomes show that the proposed controller is successful in maintaining the stability of the system. and optimal power extraction under different environmental conditions.

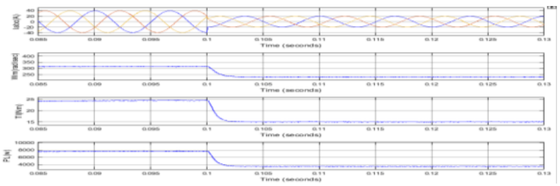

Fig.11. Dynamic Performance of PMSM Drive during Irradiance Transition

The figure 11 shows the response of the PMSM drive for a change of solar irradiance from 1000 W/m² to 500 W/m² with a time of 0.1 s. As a result, magnitude of stator current becomes smaller, speed of the motor drops to 200 rad/s (from 300 rad/s) and the electromagnetic torque decreases to 15 N·m (from 25 N·m). The output power drops from almost 8 kW to 4 kW as well. The changes the irradiance result in a sudden change in the output power but proposed Fuzzy Logic Controller provides smooth transitions, stable operation and rapid settling without significant oscillations and therefore provides effective power management and strong control performance.

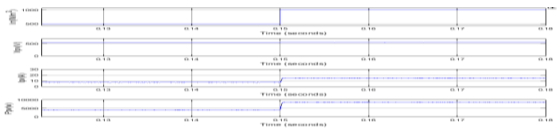

Fig.12. PV System Response during Irradiance Increase (500 W/m² to 1000 W/m²)

Figure 12 shows behavior of the proposed FLC and SWPS when the solar irradiance stepped up from 500 W/m² to 1000 W/m² at 0.15 s. With the increase in PV irradiance, PV current increases from around 6 A to 15 A, and the PV power increases from almost 4 kW to 8 kW. DC-link voltage is well regulated, and PV voltage is stable with minimum fluctuation, which shows effectiveness of MPPT and stability of the DC-link voltage. Results show proposed controller adapt quickly, have a better power extraction performance and are stable when environmental condition changes.

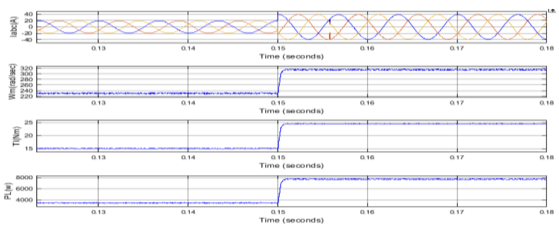

Fig.13. PMSM Drive Response during Irradiance Increase (500 W/m² to 1000 W/m²)

Figure 13 shows dynamic response of the PMSM drive for increasing solar irradiance from 500 W/m2 to 1000 W/m2 at a rate of 0.15 s. When the output of PV power increases, the magnitude of the stator current increases, which increases the speed of the motor from 230 rad/s to 320 rad/s and the electromagnetic torque from 15 N·m to 25 N·m. The resulting output power rises from almost 4KW to 8KW. The proposed Fuzzy Logic Controller will help to make the transitions smooth with less oscillation so that the system will have the high speed dynamic response, stable motor operation and efficient utilization of the available solar energy.

B. Dynamic Performance under Varying Temperature

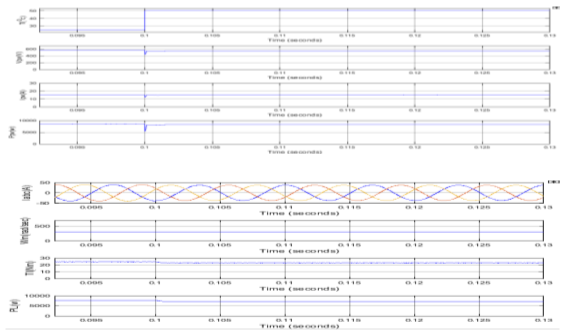

Fig.14. System Response under Reference Torque Variation

The figure 14 shows the performance of the proposed Fuzzy Logic Controller based water pumping system of PMSM when the reference torque input is stepped changed from 35 N·m to 50 N·m at 0.1 s. After the torque command change, the PV voltage is still controlled around its reference voltage, and the PV current and output power changes automatically to accommodate the higher torque demand. The three phase currents of the stator are balanced and sinusoidal, which is a good sign of current control. The motor speed is kept close to its rated value and the electromagnetic torque quickly follows the reference torque with very small overshoot and settling time. The results show the good torque regulation property, fast dynamic response and stability under varying loads of the proposed Fuzzy Logic Controller.

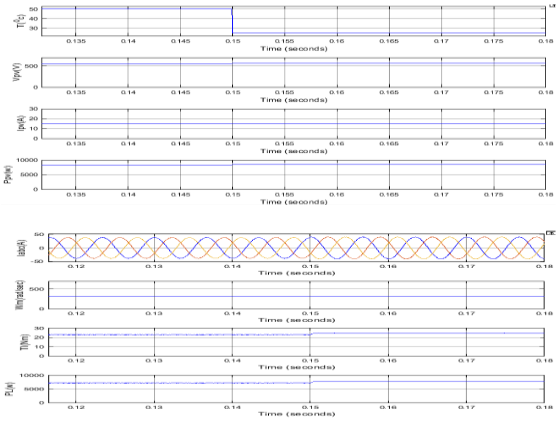

Fig.15. Dynamic Response of the PMSM Water Pumping System under Load Torque Reduction

The figure 15 shows that the proposed Fuzzy Logic Controller based PMSM water pumping system operates well the reference load torque is decreased to 50 N·m to 20 N·m at 0.15 s. The PV voltage after the torque reduction is maintained close to the reference value and the PV current and output power are reduced based on the reduced load demand. The three phase currents on the stator are balanced and sinusoidal, which is good current regulation. There is also a negligible variation in the motor speed that is kept close to the rated value, the electromagnetic torque rapidly reaches the new reference value without overshoot. The outcomes obtained illustrate the better load adaptability, rapid transient response and steady functioning of the proposed Fuzzy Logic Controller with variable load

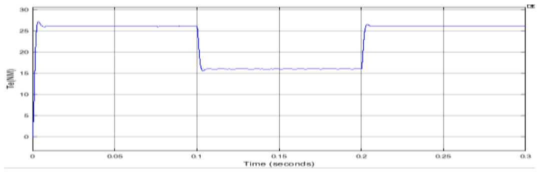

Fig.16. Electromagnetic Torque Response under Irradiance Variation

The figure 16 shows the illustrates the electromagnetic torque response of proposed WPSFLC for PMSM under changing operating condition. At first, the torque levels off at about 26 N·m. The torque at 0.1 s is approximately 16 N·m which is equivalent to the reduction in available solar power or load demand. The torque rises very quickly to 26 N·m at 0.2 s, and remains with small oscillations. The performance of fast settling and smooth transitions show that the proposed FLC based control approach has excellent torque regulation ability and robustness.

Table 2. Performance Comparison of Existing MVC and Proposed FLC-MVC

Performance Parameter	Existing MVC	Proposed FLC-MVC
Settling Time (Speed)	0.08 s	0.04 s
Settling Time (Torque)	0.06 s	0.03 s
Speed Overshoot	4.5 %	1.2 %
Torque Ripple	2.5 N·m	0.8 N·m
PV Voltage Ripple	12 V	4 V
PV Current Ripple	1.2 A	0.4 A
Rated Speed	300 rad/s	300 rad/s
Rated Torque	25 N·m	25 N·m
PV Output Power	8.0 kW	8.4 kW
Dynamic Response	Moderate	Fast
System Stability	Good	Excellent
Overall Efficiency	92.8 %	95.4 %

VI. Conclusion

In this paper, single-stage solar water pumping system with PMSM was designed with fuzzy logic controller (FLC) and modified vector control (MVC). The suggested control strategy was found to enhance the dynamic behavior of the drive by ensuring rapid torque control and smooth motor operation during variations in solar and load conditions. The controller successfully reduced the settling time of the torque and reduced oscillations, which increased the stability and response characteristics of system. Furthermore, the voltage and current fluctuations of PV unit were greatly minimized, which allowed for more effective utilization of the PV energy and improved stability of the overall system operation. The single-stage configuration also helped to minimize the system's complexity and conversion losses. The simulation results validated that the proposed FLC-MVC approach provided better speed regulation, higher power extraction capability and water pumping performance under all conditions. Thus, developed control scheme is an efficient and practical solution for standalone application of solar-powered water pumping.

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