A comparative analysis with different MPPT modules integrated for efficient PMSM drive solar water pumping system

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Abstract. This paper proposes a solar PV fed water pumping system driven by a PMSM.. A unidirectional power flow control for the same is developed and realized through a power factor corrected (PFC) boost converter. In order to improve its performance, both during dynamic and steady state conditions, the presented controller introduces a FLC, which processes the speed error. The speed along with the processed output is inputted to the PI controller for speed control of PMSM. This topology uses a solar photovoltaic (PV) array to convert the solar power into electrical power. The energy obtained is utilized to rotate the PMSM using a 3-ϕ voltage source inverter. The power quality standards required at the PV source are met by the developed control. The boost converter controller is updated with P&O MPPT replacing INC MPPT algorithm improving the performance of the system. The MATLAB/Simulink based simulations and the performance analysis are carried out to demonstrate the applicability of the system.

Keywords: PV (Photo Voltaic), PMSM (Permanent Magnet Synchronous generator), FLC (Fuzzy logic controller, P&O (Perturb & Observe), INC (Incremental Conductance), MPPT (Maximum Power Point Tracking). MATLAB/Simulink.

I. INTRODUCTION

The rising energy crises throughout the world and pollution of natural habitats, have been seeking attention from engineering and science fraternity since couple of decades. The knowledge for manifestation of renewable energy sources into useful form, has been maturing rapidly. The advent of fast switching power electronic devices and development in semiconductor technology, have majorly contributed to energy conversion methods. The renewable energy utilization, which started from converting the energy of running water, has travelled across to convert solar energy to electrical energy directly today.

Solar photovoltaic (PV) energy converters earlier have been inefficient with the efficiency as low as 5-6 % and highly costly [1]. However, with increased technological research and advancements, the efficiency of PV array, at present, has reached 15-16%. Moreover, the prices have been reducing gradually. Today, PV energy conversion is viewed as one of the promising alternatives to fossil fuel based electricity generating systems, as there are no toxic emissions, no greenhouse gases emission, no fuel cost involvement, least maintenance cost, no water use etc. However, the technology is in developing phase and there are many challenges which need to be addressed such as, intermittency, high initial cost and low efficiency. The solar water pumps [2]-[4] are gaining the popularity in rural areas, where the electricity is not available. Moreover, solar PV fed water pumps are the favored in remote areas for irrigation, water treatment plant, and agriculture purpose. Country like India, where 70% population depends upon agriculture, therefore, irrigation is necessary for good yield. There is large number of water pumps in the world running with electricity or with non-renewable energy sources. The acquisitions of solar PV based water pumping systems [5] are more convenient as compared to diesel based water pumping systems in respect to the cost and pollution. The design of a motor drive system powered directly from a PV source, demands creative solutions to face the challenge of operation under variable power restrictions and still maximize the energy produced and the amount of water pumped [6].

In PV pumping (PVP) systems, a PMSM shows good performance as compared to other commercial motors because of its rugged construction. The evolution is intended to develop productive, reliable, maintenance-free and cheap PV water pumping system [7]. However, new permanent magnet motors such as brushless DC motor and permanent magnet sine fed motors are used into pumping, but are still overshadowed by PMSM because of cost and availability constraints [8]. Moreover, the manufacturing of the PMSM is in matured stage giving an edge to its use in developing countries for solar water pumping application. With the emergence of outperforming solid state switches, high speed processors and efficient motor control algorithms, IMD based water pumping systems have taken a step ahead to conventional water pumping systems. Moreover, PV array fed IMD has performed ruggedly in the field of pumping system by utilizing a VSI (Voltage Source Inverter). The proposed work deals with a three-phase IMD for solar water pumping, which meets the requirement of life without electricity in remote locations.

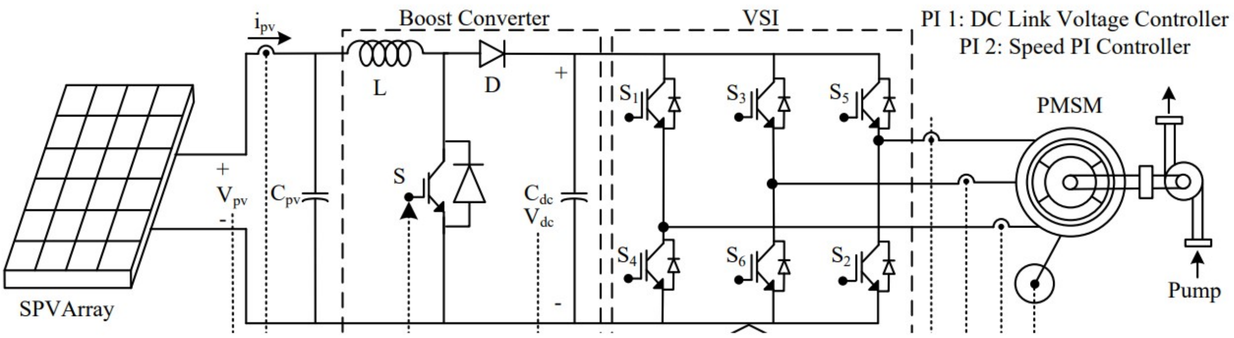

Figure 1: Proposed system with PMSM drive by solar PV array

This work presents a solar PV array powered PMSM driven solar water pumping system. The presented topology utilizes a hybrid PI controller for speed control of PMSM and an INC based MPP tracking for optimum power extraction from solar PV array. The hybrid PI controller is a combination of FLC and PI controller. The FLC modifies the speed error in accordance to its magnitude and direction. The modified error along with the speed error is inputted to the PI controller and thereby the speed of the PMSM is controlled. The presented controller improves the dynamic as well as steady state response of the solar water pumping system. The complete system along with the presented controller, is modelled and simulated using MATLAB/Simulink Simscape Sim power system toolbox.

II. INC AND P&O MPPT ALGORITHM

In incremental conductance (INC) algorithm, the controller measures incremental changes in PV array voltage and current to predict the effect of a voltage change. This method requires more computation in the controller, but can track changing conditions more quickly than the P&O algorithm [21, 22]. Like the P&O algorithm, it can produce oscillations in output power. This technique utilizes the incremental conductance ($\Delta I/\Delta V$) of the PV array to calculate the sign of the variation in power with respect to voltage ($\Delta P/\Delta V$). The INC algorithm calculates the maximum power point by comparison of the incremental conductance ($\Delta I/\Delta V$) with the array conductance (I/V). When these two are the same ($\Delta I/\Delta V = I/V$), the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated. The INC algorithm is based on the fact that at the maximum power point $\Delta P/\Delta V = 0$ and P = VI. Incremental conductance algorithm has only two sensors, voltage and current sensors, which are required in order to measure the PV device output voltage and current [23]. The flowchart for implementation of the INC algorithm is depicted in Fig. 2. The corresponding equation that mathematically describes the INC algorithm can be expressed as follows: The output power from the source can be written as follows:

P=V·I.P=V·I (1)

The fact that P=V·IP=V·I and the chain rule for the derivative of products with respect to voltage yield:

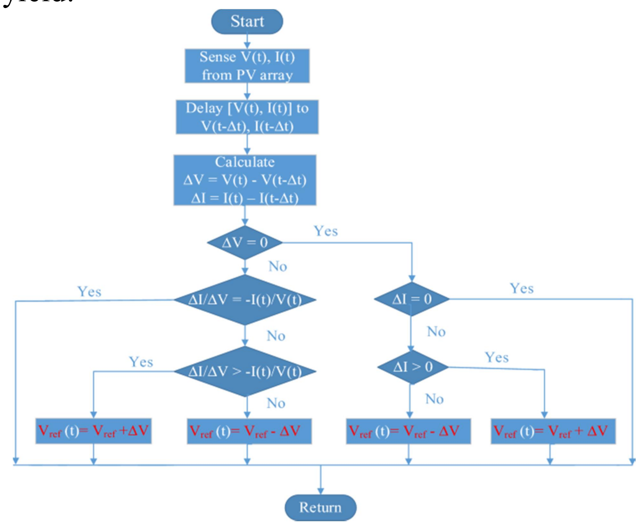

Figure 2: Flowchart of the INC algorithm

Figure 3 depicts the flowchart for implementation of the P&O algorithm; first, the practical voltage and current from PV array are measured. After that, the product of voltage and current gives the actual power of PV module. Then, it will check status what whether $\Delta P = 0$ or not. If this status is satisfied, then operating point is at the MPP. If it is not satisfying, then it will check another status that $\Delta P > 0$. If this status is satisfied, then it will check out that $\Delta V > 0$. If it is satisfied, then it indicates that operating point is at the left side of the MPP. If $\Delta V > 0$ status is not satisfied, then it indicates that operating point is at the right side of the MPP. This process is continuously repeated until it reached the MPP. So, at all times there is a compromise between the increments and the sampling rate in the P&O algorithm.

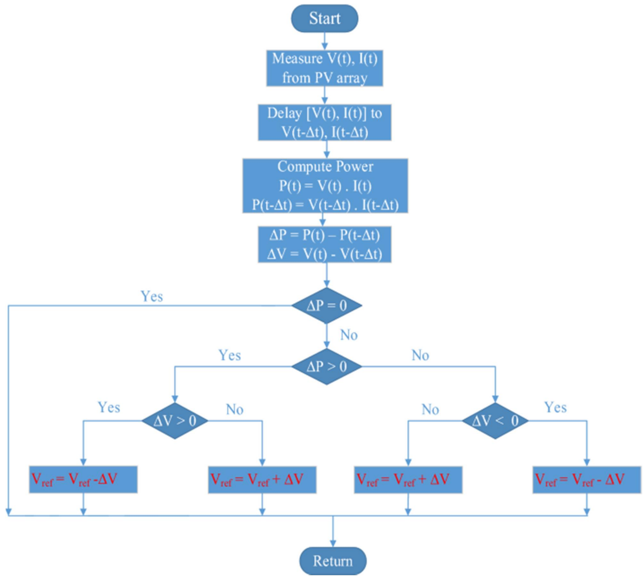

Figure 3: Flowchart of the P&O algorithm

The PV generator output is required to contain a DC–DC converter to set the solar modules output voltage at the desired value in order to track the MPP. The power converters are the devices widely used in many industrial applications. The three topologies which are more popular are the buck, boost and buck–boost power converters. These topologies have several properties depending on the connection between their devices. In this paper, the boost converter topology is used because its free-wheeling diode can be used for blocking reverse current and it efficiently amplifies PV array output voltage to higher value and is controlled by pulse width modulation (PWM) switch.

III. PMSM DRIVE CONTROL

In the presented topology, the reference speed (ω*) is generated in two parts. First part comes from DC link voltage controller whereas second part comes from solar PV power feed-forward term. The ω* is compared to actual speed (ωr) to generate a speed error (ωe). ωe along with change in ωe (Δωe) is inputted to the fuzzy logic controller (FLC) to generate another speed error (ωe flc) based on the intelligence of the FLC in order to compensate for system non-linearities. Both the errors are summed up to generate modified speed error (ωe mod), which is inputted to the speed controller. The schematic diagram for the hybrid speed control is presented in Fig. 4.

The DC link voltage error at kth sample, is expressed as,

$$V\ e\ (k) = V\ (k) - V\ (k)\ * \qquad (2)$$

This voltage error is inputted to DC link voltage controller. The DC link voltage controller minimizes this error by adjusting its output and its output considered as ω1 * (k). ω1 * is expressed as,

$$\omega\ *\ (k) = \omega\ *\ (k-1) + Kp\ \{V\ (k) - V\ (k-1)\} + Ki\ \{V\ (k) - V\ (k-1)\} \qquad (3)$$

Where, Kpd and Kid are proportional and integral constants, respectively utilized in DC link voltage controller. ω2* (k) is generated from PV power feed-forward term such that,

the speed control is attained using vector control. After the generation of ωe mod, it is inputted to the speed controller. The speed controller output is considered as reference quadrature axis current (Iq*). The speed controller minimizes ωe mod to zero by adjusting Iq*.

Iq* is expressed as,

$$I\ *\ (k) = I\ *\ (k-1) + K\ \{\omega\ (k) - \omega\ (k-1)\} + K\ \omega\ (k) \qquad (4)$$

Where, Kpω and Kiω are proportional and integral constants, respectively utilized in speed controller. Since for solar water pumping, the pump speed needs to be controlled below base speed, therefore no field weakening is required. Hence, Id * is kept zero. Using an inverse Park's transform (dq0 to abc), the reference stator currents of PMSM (ia * , ib * and ic *) are evaluated from Id * and Iq * . The sensed motor phase currents ia, ib and ic and the reference currents ia * , ib * and ic * are inputted to the hysteresis controller, which generates gating signals for VSI.

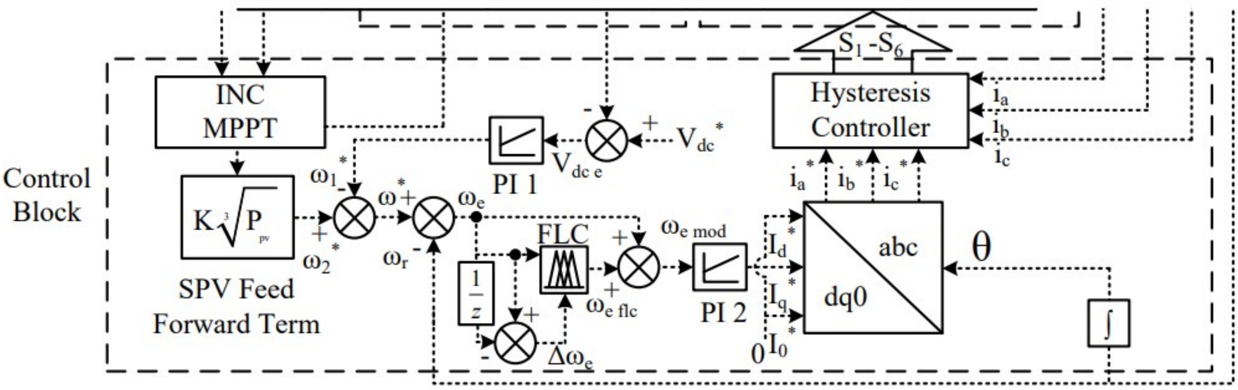

Figure 4: Proposed controller

IV. SIMULATION RESULTS

The model of stand-alone solar PV based PMSM drive system for water pumping application is developed using MATLAB/ SIMULINK R2010. The performance of the PV based PMSM drive system for water pumping application is evaluated under various operating conditions and observed in terms of PV voltage (VPV), PV currents (IPV), PMSM currents (Imabc), PMSM speed (N), electromagnetic torque and load torque (T,Tl), DC link voltage (Vdc) and mechanical power (Pm).

Fig. 5 shows the performance of solar PV based PMSM drive under step change in irradiation. At 1s, a step change in PV radiation from 1000 to 700 W/m2. It leads to instantaneous change in electromagnetic torque of PMSM due to which the PMSM starts decelerate and it is achieved the desired speed within 20 ms. The time require to achieve steady state point is reasonably small.

However under such transient conditions, the DC link voltage remains fairly constant and necessary changes in stator currents are also monitored to maintain power balance between input supply and load. It is observed that as irradiance decreases, PMSM speed fall. It is also observed that at very low value of radiation, input and output power are also very less in accordance with characteristics of solar PV.

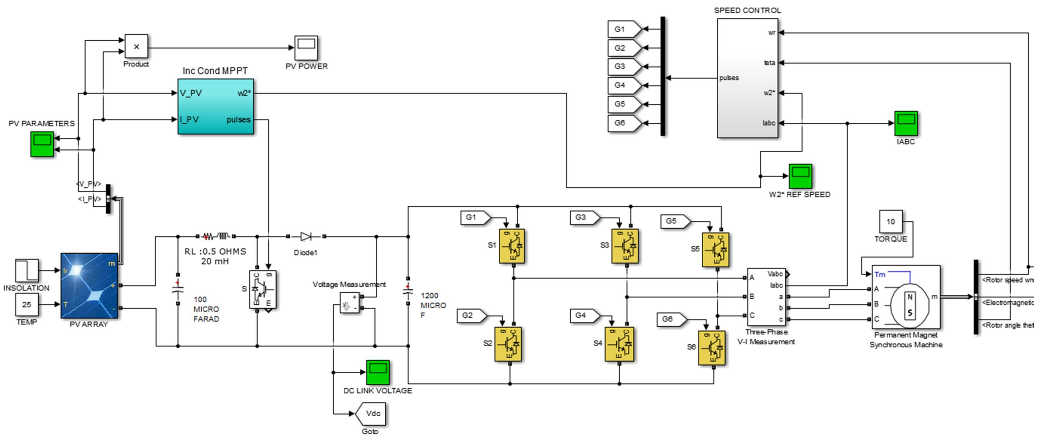

Figure 5: Test system modeling

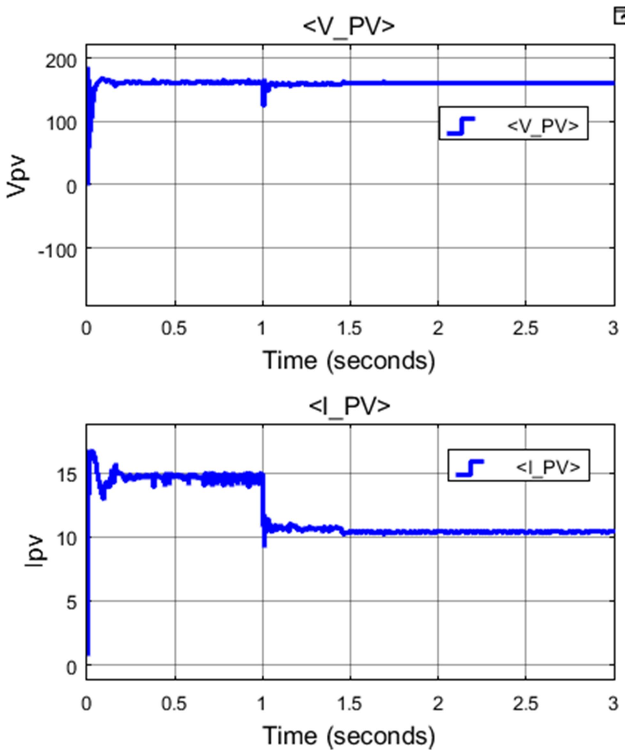

Figure 6: PV array characteristics

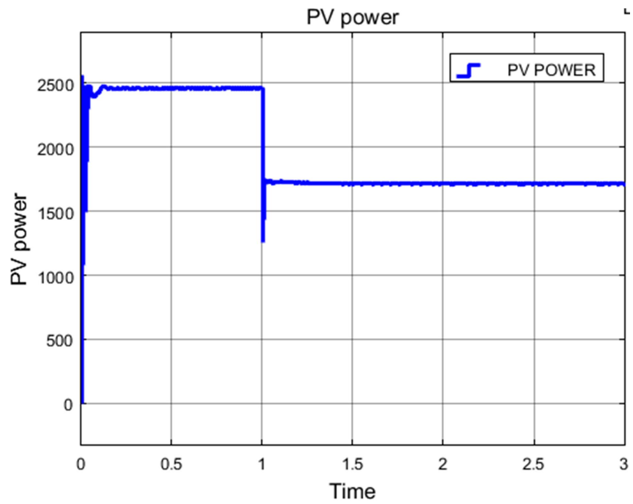

Figure 7: PV power generated

The above are the characteristics of the PV panel defining the voltage, current and power of the PV array module. The below figure 8 is the boosted voltage as per the change in irradiation. As observed in above figure the power of the PV array is dropped from 2.5kW to 1.7kW at 1sec when the irradiation is dropped.

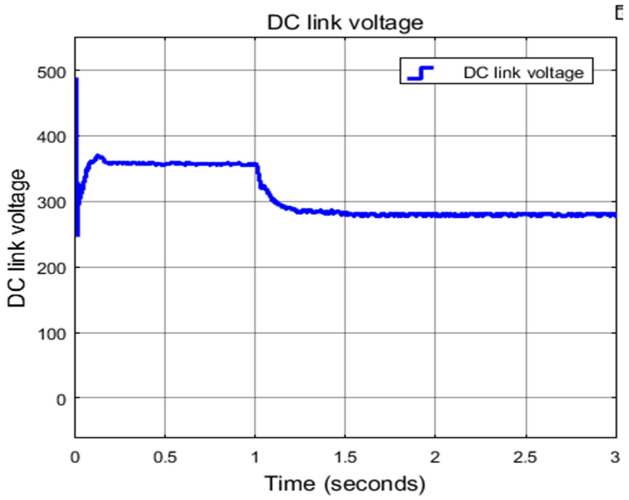

Figure 8: DC link voltage output of boost converter

As per the change in irradiation the change in reference speed is generated as in figure 9.

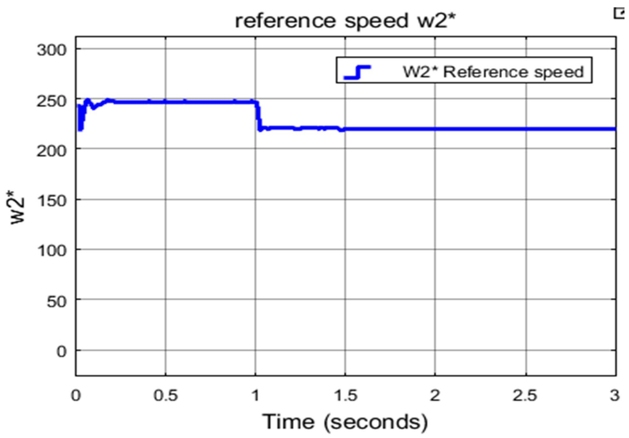

Figure 9: Speed reference signal

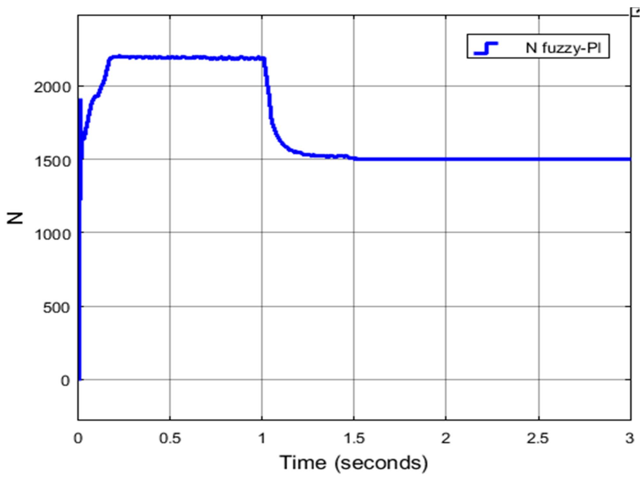

Figure 10: Speed of the PMSM as per reference

With respect to change in reference speed the measured speed of PMSM is shown above in figure 10. The speed is dropped from 2200rpm to 1500rpm with respect to drop in solar irradiation. Throughout the simulation time of 3sec the electromagnetic torque is maintained at 10Nmt as per the given input load torque shown in figure 11 below.

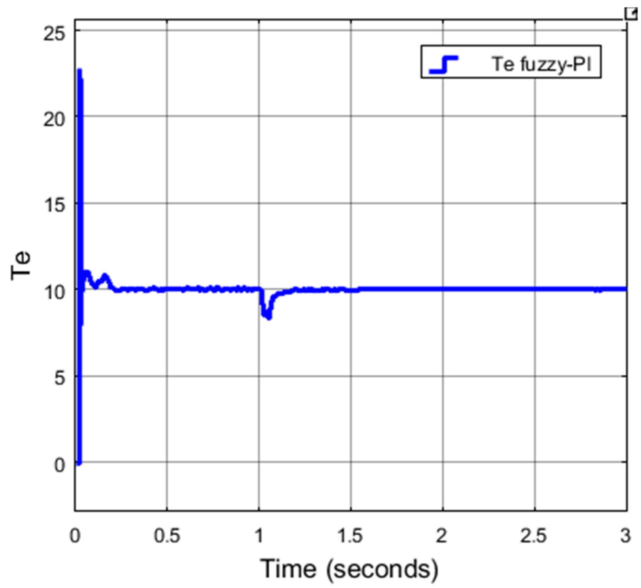

Figure 11: Electro-magnetic torque Tem of PMSM

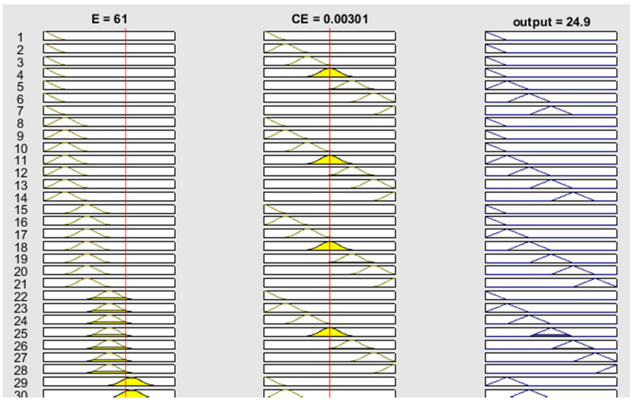

Figure 12: Fuzzy rules

The fuzzy rules of the 49 rule base can be seen in figure 12 generated with respect to error current input. The below figure 13 is the stator currents of the 3-ph PMSM.

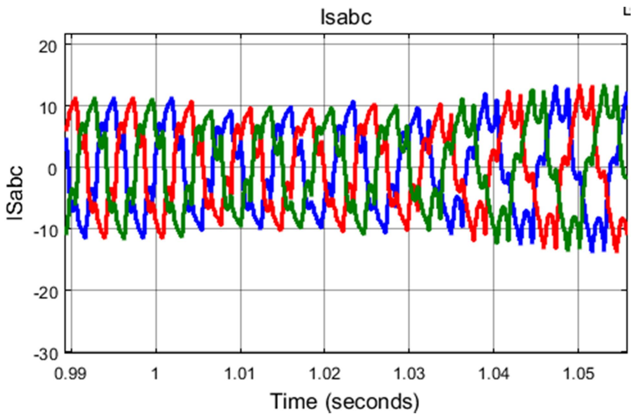

Figure 13: Stator currents of PMSM

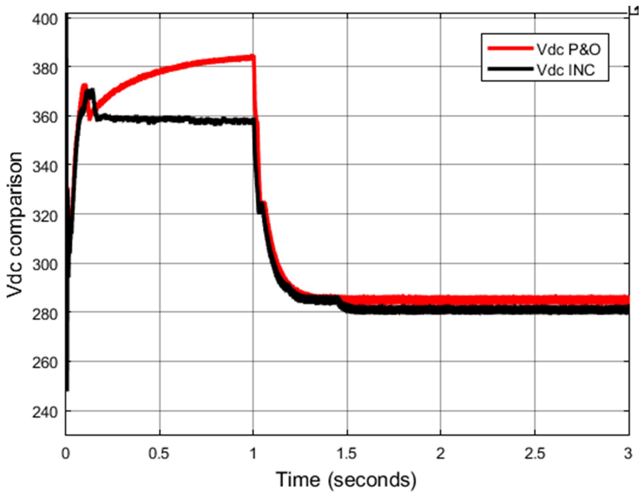

Figure 14: DC link voltage comparison between P&O and INC MPPT

When the INC MPPT is updated with P&O MPPT the above figure 14 is the DC link voltage magnitude comparison. The voltage magnitude is improved to 380V from 360V during initial condition making the operating condition of the PMSM better. After the drop in solar irradiation the voltage is more stable for the P&O MPPT algorithm control as compared to INC MPPT control.

V. CONCLUSION

A stand alone solar PV system has been modeled for the PMSM drive used in water pumping system. Solar PV water-pumping systems are simple, reliable, conserve energy and need less maintenance. It has been demonstrated that proposed system provide satisfactory control on motor speed for water pumping under wide change in solar irradiation. The speed reference of the controller is adjusted as per the change in solar irradiation and the PMSM is speed is adjusted as per the reference signal. The DC link voltage is more stable when operated with P&O MPPT and the magnitude is also increased.

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