International Transaction on Power and Energy Systems

ISSN No:XXXX-YYYY, www.itpes.in

Article

Design and Implementation of Standalone Solar PV fed Induction motor drive for Water pumping application

Premkumar K[1],*, Shyam D[2] and Sivamani D[3]

[1]Department of Electrical and Electronics Engineering, Rajalakshmi Engineering College, Chennai, Tamil Nadu; premkumar.k@rajalakshmi.edu.in
[2]Department of Electrical and Electronics Engineering, Rajalakshmi Engineering College, Chennai, Tamil Nadu; shyam.d@rajalakshmi.edu.in
[3]Department of Electrical and Electronics Engineering, Rajalakshmi Engineering College, Chennai, Tamil Nadu; sivamani.d@rajalakshmi.edu.in

***** Correspondence: premkumar.k@rajalakshmi.edu.in; Tel.: +91-9786992345

Received: 20.10.2020; Accepted: 28.01.2021; Published: 28.01.2021

Abstract: Implementation of Solar PV fed Induction motor drive for water pumping system is demonstrated for standalone systems in this paper. The challenges encountered during the implementation of solar PV based pumping systems are to design a low-cost low power module for farmers in developing countries like India. The number of PV modules used for low power applications should be calculated in order to bring down the initial cost of the system. This module comprises of two staged process where the first stage focuses on tapping of maximum power from the PV module by varying the duty ratio of DC-DC converter. In order to control the duty ratio of the converter, Maximum power point tracking (MPPT) with an incremental conductance method (ICM) is used in the proposed system. The second stage comprises of an induction motor drive with standard frequency converter strategy across the load. The simulation and hardware prototype is carried for standalone system which is incorporated for water pumping system.

Keywords: Photovoltaic; Pulse Width Modulation; Water Pumping System; Standard Frequency Converter; Maximum Power Point Tracking; Voltage Source Inverter; Induction Motor Drives.

---

1. Introduction

As per the latest census survey, almost around 700 million people across different countries face the does not have the basic necessity to live their lives. Every year this ratio is continuously increasing with increase in population. Every human need food and water for survival. Most of the underdeveloped countries face severe food and water scarcity. By 2025, almost 1.8 billion people across the world would face water scarcity. This indicates two-third of the overall population would face water scarcity. According to Composite Water Index (CWI) taken on 2018, India's overall economic GDP would be lost by six percentages around 2050. Due to varying climatic condition, many parts of the world face severe drought condition due to lack of rain. Water and food demand in India would exceed the available resource by 2030. This condition would still worsen due to high population rate. The primary function is to provide the people with groundwater resources which need to be pumped for their daily needs and to irrigate the fields for food. With the increasing cost of fuel and demand for power in rural areas, farmers need to find an alternative solution to solve their needs.

Photovoltaic (PV) based water pumping systems (WPS) would be a possible solution for the above-mentioned problems. The farmers need not depend on the grid power to water their plants rather than they can provide their own developed power from PV source [1]. During the initial stages of PV based water pumping system, DC motors are generally used. Later DC motors are replaced by Induction motors due to ruggedness, high reliability and efficiency with lower maintenance cost. The PV fed Induction motor drive are more reliable when compared to conventional diesel pumps used for irrigation purpose because it requires less maintenance cost and low pollution level [2]. The overall staging of PV module is influenced based on the critical factors to maximize the output power using maximum power point tracking techniques (MPPT) such as nature and capacity of load used, irradiation level, cell operating temperature, shading factor [3].

The output of the PV system is extract to maximum power level by various MPPT techniques. Among various classification of MPPT algorithm, it is grouped in three major functionality methods: (i) First major classification uses conventional methods like Perturb and Observe method (P&O) [4], Constant Voltage Controller method, Incremental Conductance method (ICM) [5]. These methods are classified based on their speed, range of readiness and their complexity level [6]-[7]. In the proposed system, Incremental conductance method (IMC) is used which overcomes the problems faced by Perturb and Observe method and also it provides better tracking power response with change in irradiation [9]. (ii) Second major classification based on Artificial Intelligence (AI) based methods like Artificial Neural Networks (ANN), Fuzzy Logic Controller (FLC)[6] which provides better response time and accuracy [8]. (iii) Third major classification focuses on Hybrid methods which incorporate the features of first and second methods together. Few reputed techniques are Proportional Integral based Fuzzy Logic controller (PI-FLC), modified Perturb and Observe based ANN network.

During the initial studies of solar water pumps which are designed are inefficient with very low efficiency of 5-7%. The main drawback is to design this low efficient converter at very high cost. Later researchers moved on to different techniques to improve the efficiency of the motor. The proposed system which operated on Induction motor drives (IMD) provided better results compared to other permanent magnet motor drives such as brushless DC motor.

2. PV based Water pumping for standalone system

The system architecture for the PV based water pumping system is designed using PV panels, DC-DC converter where the gating pulses were generated using MPPT algorithms, voltage source Inverter connected with centrifugal pump driven by Induction motor drive which is shown in Figure 1.

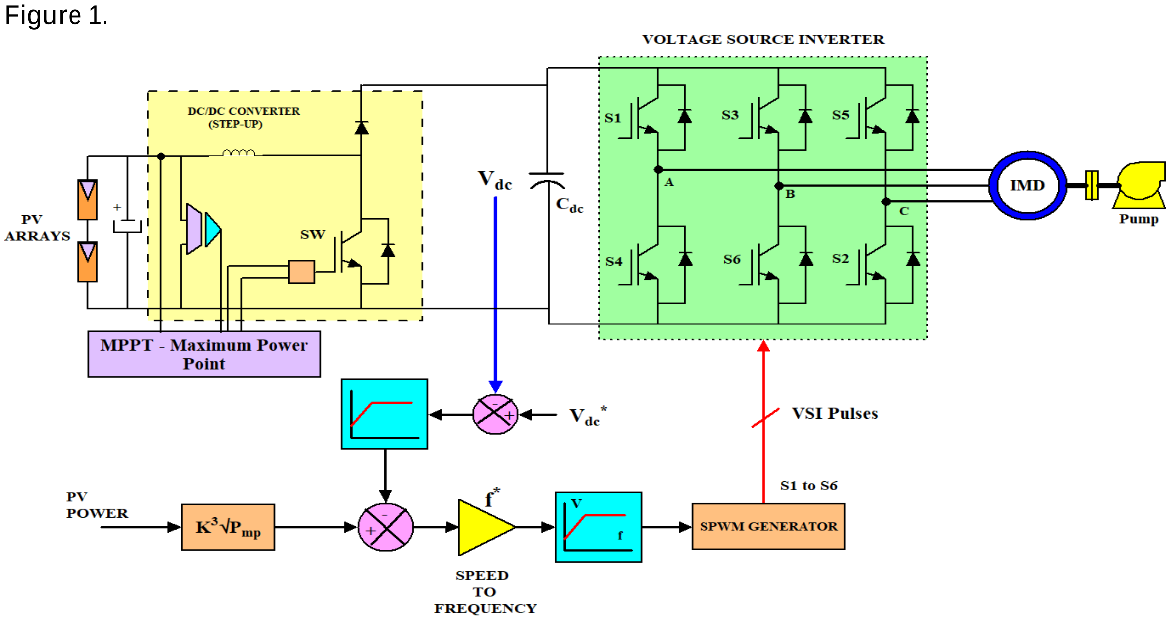
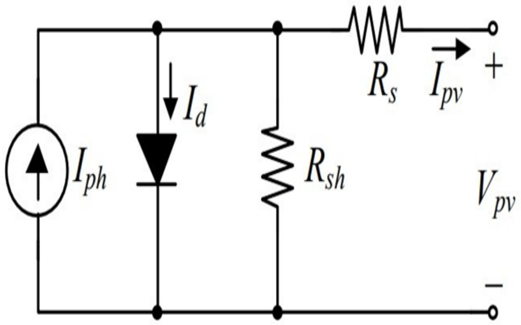
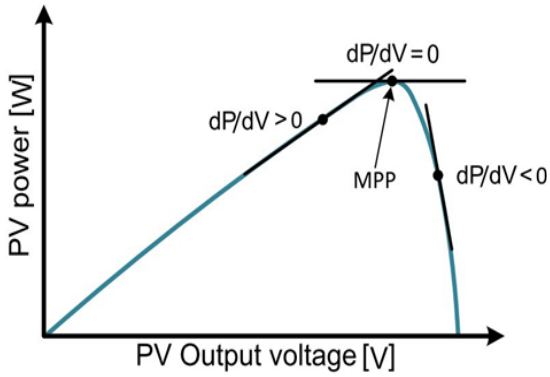


Figure 1. System architecture for PV based Water pumping for standalone system

The system architecture incorporates one DC/DC converter and voltage source Inverter (VSI) to achieve maximum efficiency. There could be an addition after DC-DC converter with DC-AC converter based on their applications needs. The pulses for voltage source inverter fed from SPWM generator which is processed through Voltage-frequency (V/f) control.V/f control improves the starting performance of motor drive and also provides smooth conduction of the motor during starting. Maximum power point is tracked by modifying the modulating frequency in order to extract maximum power from Induction motor drive (IMD) through PV arrays. The equivalent circuit model of PV array is shown in Figure 2(a) and a characteristic of PV curve is shown in Figure 2(b).





(a) Equivalent circuit model of PV array (b) PV curve

Figure 2. Equivalent circuit and characteristics of solar PV array.

3. Design calculation for the proposed module

3.1. Design implementation of Solar PV array

The calculation of PV array should be done first by keeping the specifications of the motor. The design should be done carefully based on the capacity of the motor. The capacity of the motor should be almost equivalent the capacity of the PV panel. The maximum power drawn from the panel for specified radiation level is denoted by P_{pv} which is obtained based on the number of series and parallel operation done during assembling. Ns denotes the number of series cell connected to the panel and Np denotes the number of parallel cells connected to the panel. V_{mpp} indicates the PV panel voltage at MPP and I_{mpp} indicates the PV panel current at Maximum Power Point (MPP).

$$P_{pv} = \left(N_s \times V_{mpp}\right) \times \left(N_p \times I_{mpp}\right) \quad (1)$$

The maximum power drawn from the panel is obtained from equation (1). The specifications of the solar panel are provided in Table 1.

Table 1. Specifications of PV Module FTS-220P

Parameters	Specifications
Cell type	Polycrystalline
Number of cells	60
STCPower drawn from the Panel (Pmpp)	220 W
Voltage at maximum power (Vmpp)	28.5 V
Current at maximum power (Impp)	7.72 A
Open Circuit voltage (V_{oc}) for single module	36.8 V
Short circuit current (I_{sc}) for single module	8.37 A
Panel Efficiency for single module	13.6%
Temperature coefficient of Pmpp	46°C ± 2°C

Table 2. Specifications of PV Array

Parameters	Specifications
Maximum power drawn from the Panel array (Pmp)	6kW
Maximum voltage from panel array (Vmp)	600 V
Array Current at maximum power (Imp)	10 A
Open Circuit voltage from the panel array (Voc)	993.6 V
Short circuit current from the panel array (Isc)	8.37 A

The overall power drawn from the PV array is taken as 6 kW where the number of modules connected in series (N_s) is 27 and number of modules connected in parallel (N_p) is taken as 1 which is indicated in Table 2.

3.2. DC link voltage calculation

The calculation of DC link voltage (V_{dc}) of voltage source inverter is obtained from the relationship based on the modulation index (M) and the line to line voltage across the motor terminal which is shown in equation (2). The calculated DC link voltage of VSI is 586.89V but in practical case it is taken as 600V.

$$V_{dc} = \frac{2\sqrt{2}}{2} \times \frac{V_{L-L}}{m} = \frac{2\sqrt{2}}{2} \times \frac{415}{1} = 586.89\,V \tag{2}$$

3.3 Formulation of DC link capacitor

DC link capacitors (C_{dc}) are used to store sufficient energy during the time of transient occurance due to sudden increase in load or change in radiation level. The value of the DC link capacitor is calculated based on fundamental frequency component which is formulated in equation (4) and (5).

$$\omega = 2\pi f_r = 2\pi 50 = 314\,rad/sec \tag{4}$$

$$C_{dc} = \frac{6\alpha V I t}{(V_{dc}^2 - V_{dc1}^2)} = \frac{6 \times 1.2 \times 239.6 \times 4.17 \times 0.005}{(600^2 - 586.89^2)} = 2311\mu F \tag{5}$$

Where α is the loading factor which is taken as 1.2, V is the phase voltage and I is the phase current across the motor and t is the transient duration. The value of the DC link capacitor is taken as 2500μF.

3.4 Specifications of DC-DC converter

DC-DC converter used in the proposed system is Step-up converter [11]. The duty cycle ratio (D) and inductor (Lm) used in the step up converter is calculated from equation (6) and (7).

$$D = \frac{V_{dc} - V_{mpp}}{V_{dc}} = \frac{600 - 586.89}{600} = 0.0219 \tag{6}$$

$$Lm = \frac{V_{mp}\,D}{\Delta I_1 f_s} = \frac{586.89\,x\,0.0219}{0.2 \times 0.74 \times 10000} = 8.68\,mH \tag{7}$$

Where ΔI_1 is the ripple current and fs is switching frequency which is taken as 10KHz. Thus the value of inductor(Lm) for step up converter is taken as 10mH.

3.5 Formulation of Water pump design

The formulation of water pump depends on the non-linear characteristics between load torque and motor speed. Load torque is directly proportional to the square of the rated motor speed (Rotor) which is shown in equation (8). The proportionality constant of the pump (K) is calculated based on the values of load torque and motor speed. The rated torque of the induction motor drive is taken as 14.69 Nm and the rated speed to the induction motor is taken as 1430 rpm. The rotional speed of the motor is denoted by ω_r [16].

$$K = \frac{T_L}{\omega_r^2} = \frac{14.69}{\left(\frac{2 \times \pi \times 1430}{60}\right)^2} = 6.55\, x\, 10^{-4}\ Nm/(rad/sec)^2 \quad (8)$$

4. Control scheme for PV based Water pumping system

4.1 Incremental Conductance Method (ICM)

The proposed control scheme for PV based water pumping system is carried in two different stages of power conversion process. First stage of process deals with the Incremental Conductance Method (ICM) for maximum extraction of power from the PV modules and the next stage of process deals with the scalar V/f control for Induction Motor drive [10].

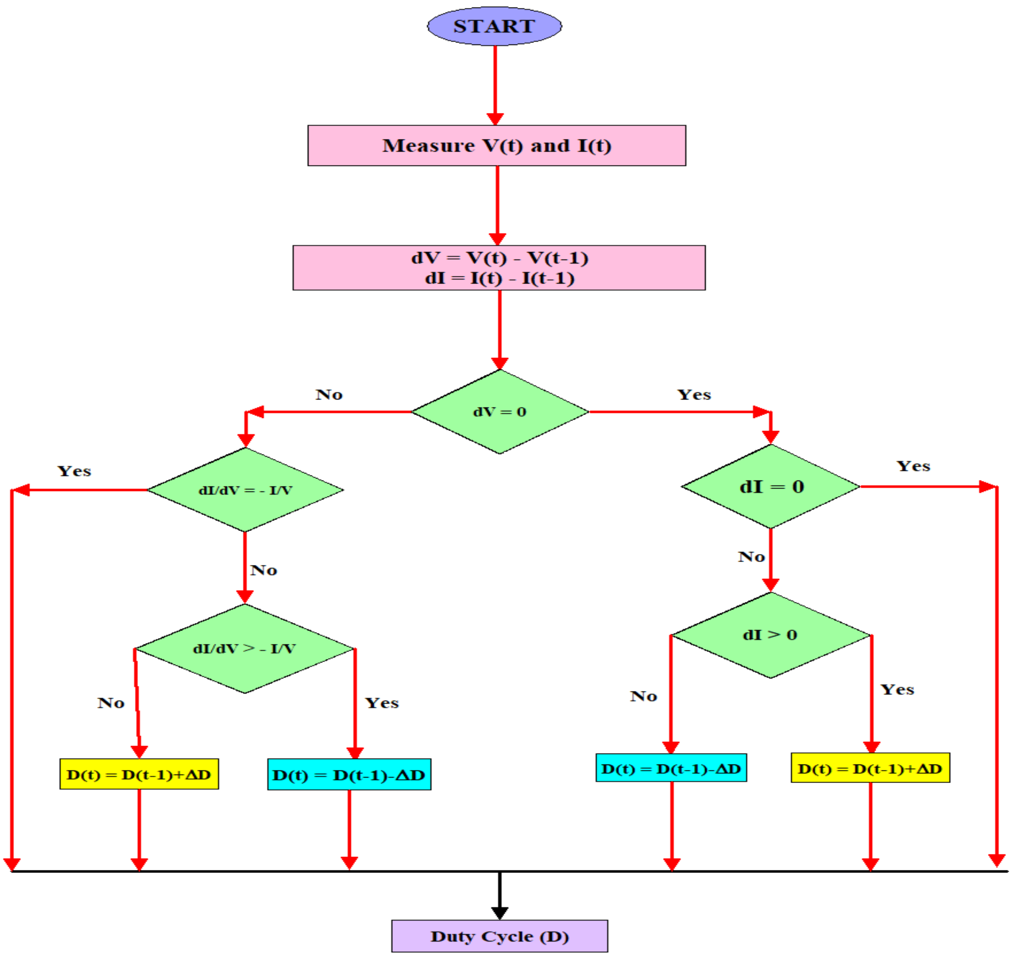


Figure 3.*Flowchart of Incremental Conductance Method*

The voltage and current from the PV array are fed to the Incremental conductance method for further processing which is shown in Figure 3. Due to variations in Power, voltage and current parameters, the algorithm chooses the best suitable duty ratio to be provided for the DC-DC converter. The output voltage of the DC-DC converter is kept constant by using Proportional Integral controller.

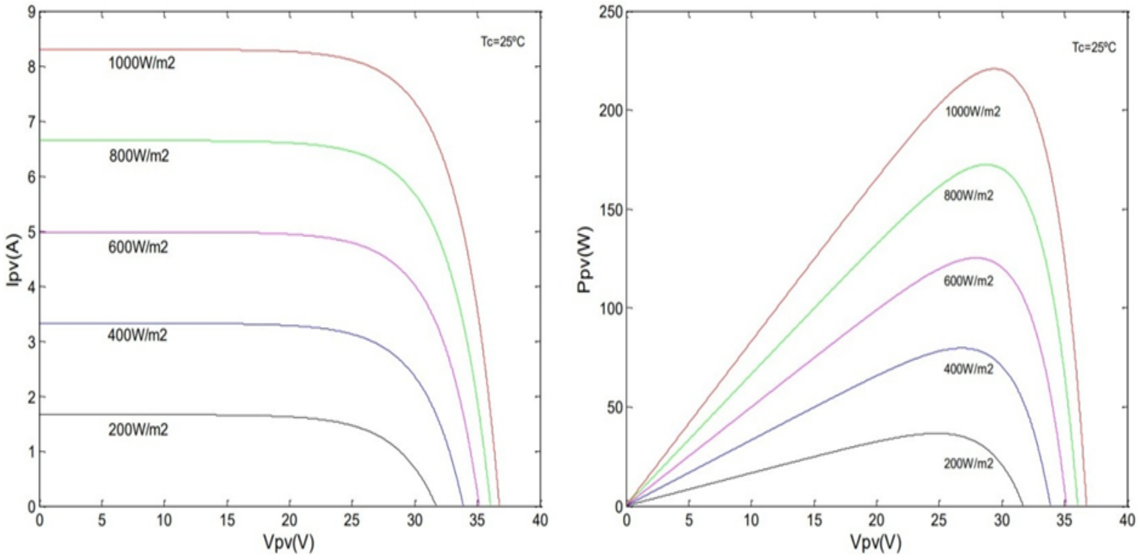


Figure 4.*FTS-220P module -I-V and P-V curves under different radiation levels*

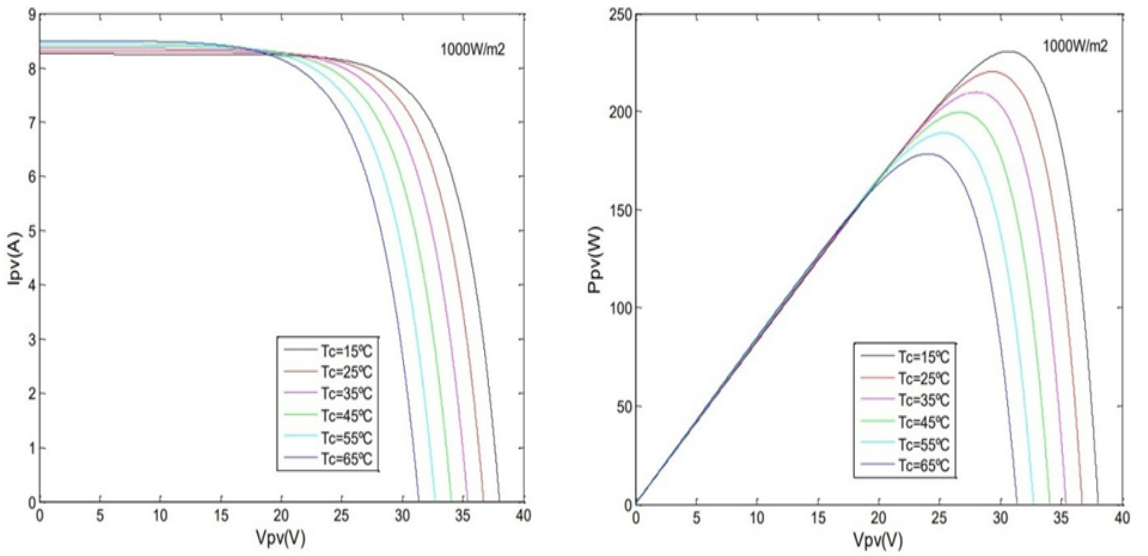


Figure 5.FTS-220P module -I-V and P-V curves under different temperature levels

The proposed system uses Incremental Conductance method to exract the maximum power from the PV panel. Figure 4 plots the I-V and P-V curves for FTS-220P module under different radiation levels and Figure 5 plots the I-V and P-V curves for FTS-220P module under different temperature variations. When the slope of the curve is positive, it indicates the MPP is on the left-hand side whereas the slope of the curve is negative when it indicates the MPP is on the right-hand side. When maximum power is transferred to the PV array, then the slope of the curve is taken as zero. Under MPP with changes in the radiation level for FTS-220P, voltage remains constant whereas current changes drastically.

$$P_{pv} = V_{mpp} \times I_{mpp}$$

Differentiating the above power equation with dV_{mpp}

$$\frac{dP_{pv}}{dV_{mpp}} = I_{mpp} + V_{mpp}\frac{dI_{mpp}}{dV_{mpp}} = 0$$

$$V_{mpp}\frac{dI_{mpp}}{dV_{mpp}} = -I_{mpp} \quad (9)$$

$$\frac{dI_{mpp}}{dV_{mpp}} = \frac{-I_{mpp}}{V_{mpp}}$$

Equation 9 provides the basic power equation which gets differentiated with respect to V_{mpp} to find the relationship between Incremental Conductance and Conductance in analyzing the sectors of the slope. Equation 10 provides the different sectors of slope from ICM algorithm.

Case 1: When slope is positive $\frac{dI_{mpp}}{dV_{mpp}} > \frac{-I_{mpp}}{V_{mpp}}$, *left side of MPP*

Case 2: When slope is zero $\frac{dI_{mpp}}{dV_{mpp}} = \frac{-I_{mpp}}{V_{mpp}}$ (10)

Case 3: When slope is negative $\frac{dI_{mpp}}{dV_{mpp}} < \frac{-I_{mpp}}{V_{mpp}}$, *right side of MPP*

4.2 Scalar V/f control stratergy

Scalar V/f control is easy to implement but complexity level is high while designing vector control method and Direct Torque Control (DTC). Implementation through V/f control improves the starting performance of motor drive even during low solar irradiation. Therefore, smooth conduction during starting of the motor is achieved even without providing high starting current using V/f control technique. The reference speed to the motor drive is provided from V/f control technique [12]. Figure 6 provides the information regarding the frequency control strategy which is incorporated in VSI fed induction motor [13],[14],[15],[16].

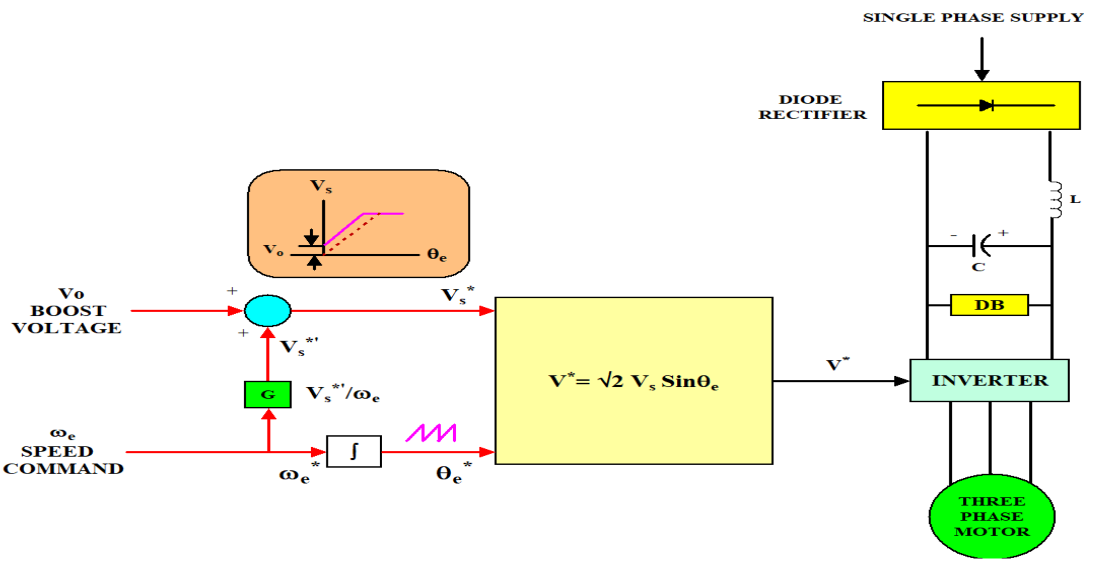


Figure 6. Scalar V/f control strategy for VSI fed Induction motor

5. Simulation Results

The proposed PV based water pumping for standalone systems is modelled and simulated using MATLAB/Simulink 2017b. The overall system is created into small subsystems in order to show the overview the simulation circuit.

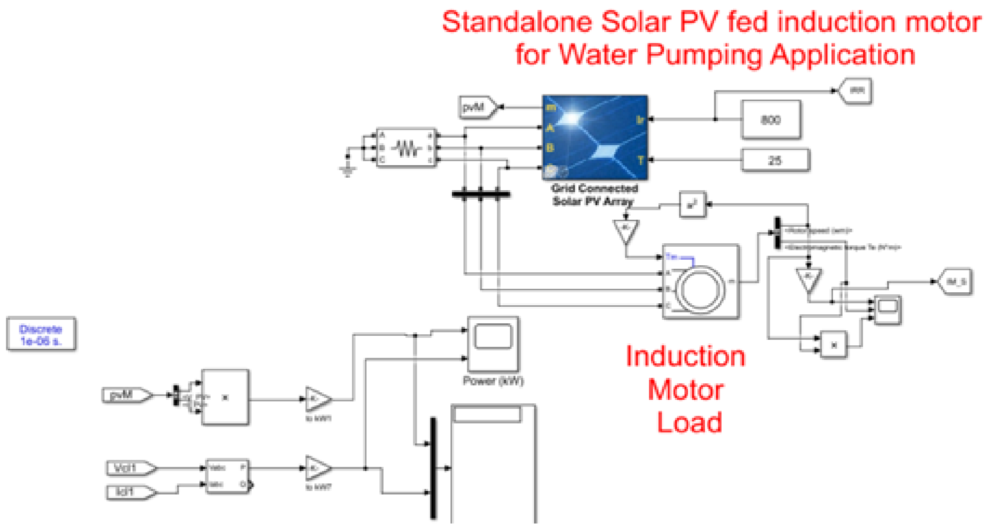


Figure 7. Simulink model of PV based water pumping system using MATLAB/Simulink

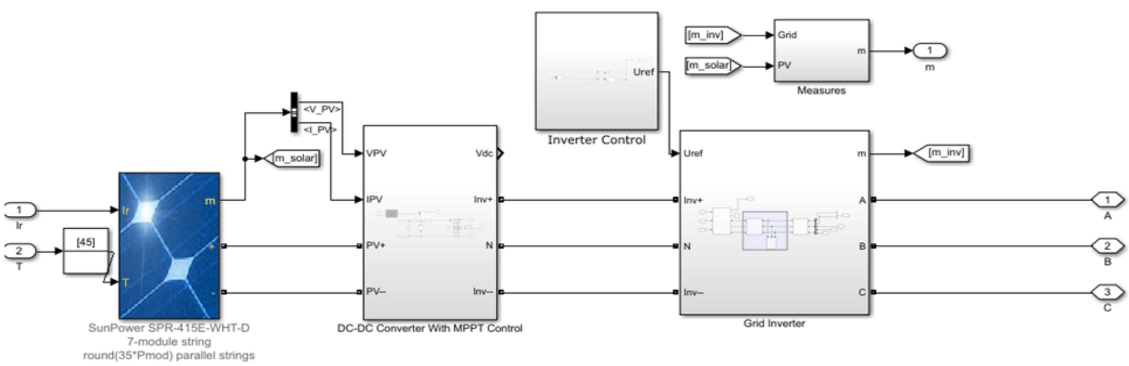


Figure 8. Subsystem model of PV array connected to DC-DC converter and VSI

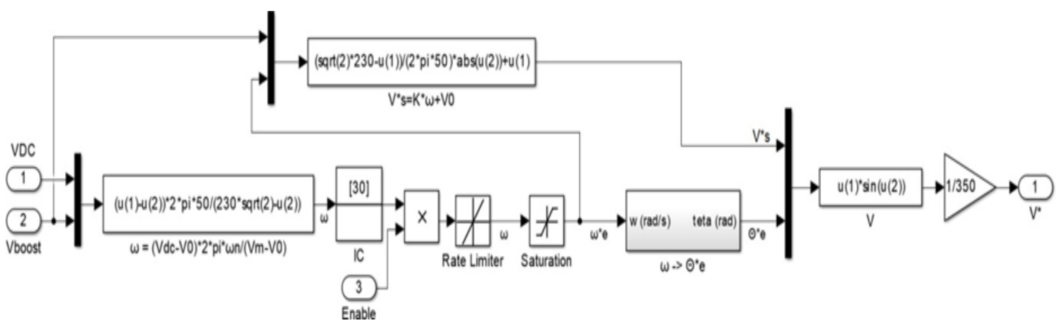
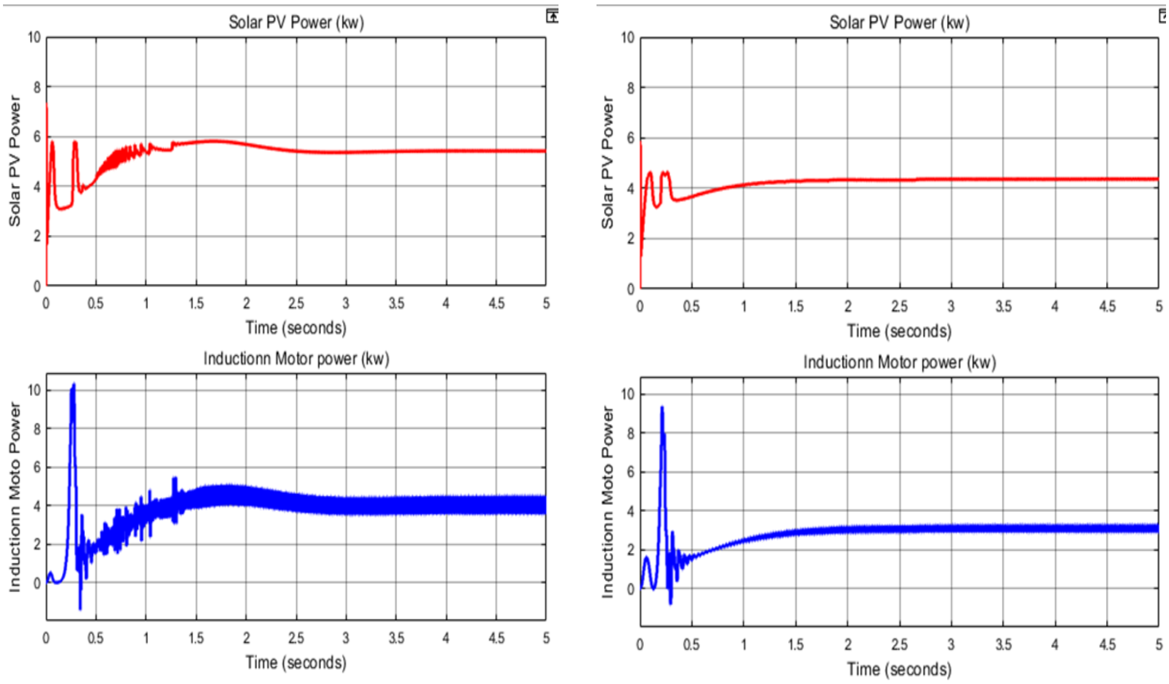


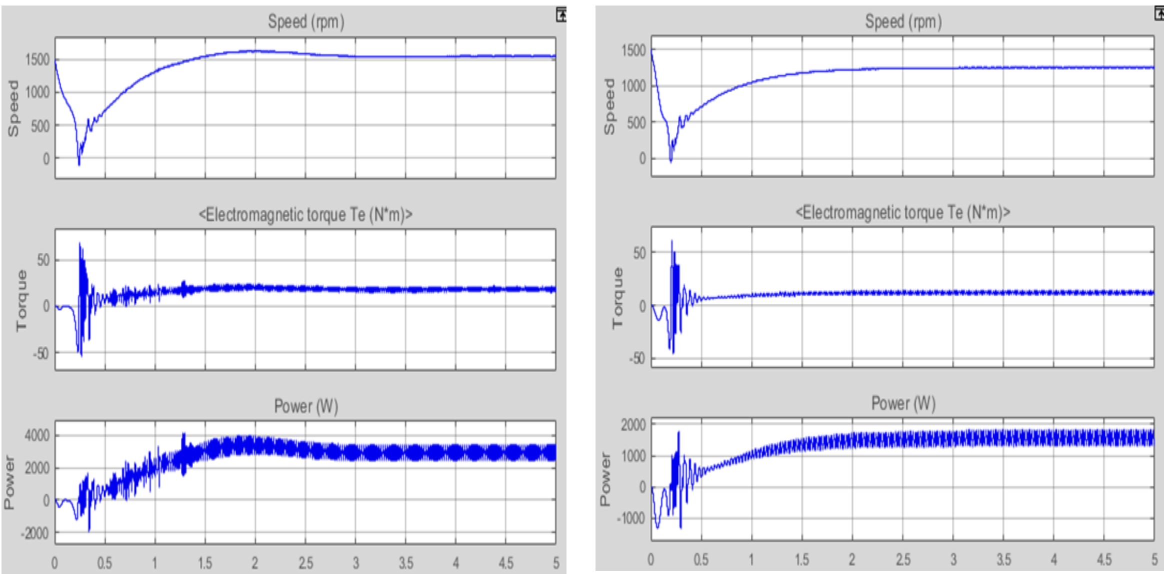
Figure 9. Subsystem model of scalar V/f control strategy using MATLAB/Simulink

The overall Simulink diagram for the proposed PV based water pumping system is shown in Figure 7. Figure 8 illustrates the output parameters of the PV array is connected to input of the DC-DC converter (Step-up) block which is again fed power to the VSI to drive the Induction motor.



(a) At 1000W/m² and 25°C (b)At 800 W/m² and 25°C

Figure 10. Simulation result of PV power and Induction motor power for different irradiance (W/m²) and temperature (°C)



(a) At 1000W/m² and 25°C (b)At 800 W/m² and 25°C

Figure 11. Simulation result of Induction motor speed, torque and power for different irradiance (W/m²) and temperature (°C)

Figure 9 provides the subsystem modelling of frequency control strategy implemented in MATLAB/Simulink. The equations are fed directly into the functional block. Figure 10 illustrates the simulation results obtained from PV power and Induction motor power for different irradiance and temperature conditions. Figure 11 illustrates the simulation results obtained from Induction motor such as speed, torque and power for different irradiance and temperature conditions. Figure 10(a) and Figure 11(a) is taken for irradiance 1000W/m^2 and temperature of 25°C and Figure 10(b) and Figure 11(b) is taken for irradiance 800W/m^2 and temperature of 25°C. From the above simulation results, Incremental Conductance method is provide better results when compared to other conventional methods. The hardware feasibility can be done for the proposed system using Incremental Conductance method.

6. Conclusions

The proposed PV based water pumping for standalone system is applicable in rural areas to satisfy their daily needs and irrigation purpose. The proposed system uses Incremental conductance method (ICM) to extract the maximum power from the PV panel and it drive the induction motor drive through DC-DC converter and Voltage source Inverter. The design calculation was done for 6 KW PV panel array for FTS-220P module. The control scheme was staged into two parts: Incremental Conductance method and Scalar V/f control strategy. Incremental Conductance method is used to find the location of MPP based on the slope. Duty ratio of the DC-DC converter is varied based on the ICM. Scalar V/f control method is used to smoothen the starting of the motor. The reference speed of the motor drive is obtained from incremental conductance MPPT. The supply frequency and switching frequency decides the nature of the PWM technique used to gate the pulses of VSI which in turn controls the speed of the Induction motor drive. The performance of the proposed system is analyzed using simulation modelling using MATLAB software. Simulation results were taken for different irradiance and temperature across PV panel and Motor drive to verify its feasibility.

References

1. Murshid, S.; Singh, B. Implementation of PMSM drive for a solar water pumping system, *IEEE Transactions on Industry Applications,* **2019,** 55(5), pp. 4956-4964
2. Singh, B.; Mishra, A.K.; Kumar, R. Solar powered water pumping system employing switched reluctance motor drive, *IEEE Transactions on Industry Applications,* **2016,** 52(5), pp. 3949-3957.
3. Ali, B. Comparative assessment of the feasibility for solar irrigation pumps in Sudan, *Renewable and Sustainable Energy Reviews,* **2018,** 81,pp. 413-420.
4. Chandel, S. S.; NaikM. N.; Chandel, R.Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies, *Renewable and Sustainable Energy Reviews,* **2015**, 49, pp. 1084-1099.
5. Shukla, S.;Singh, B. Single-Stage PV Array Fed Speed Sensorless Vector Control of Induction Motor Drive for Water Pumping, *IEEE Transactions on Industry Applications,* **2018,** 54(4), pp. 3575 – 3585
6. Alice Hepzibah, A.; Premkumar, K. ANFIS current–voltage controlled MPPT algorithm for solar powered brushless DC motor-based water pump, *Electrical Engineering,* **2020**, 102, pp. 421–435
7. Simon Meunier;Loïc Quéval;Arouna Darga;Philippe Dessante;Claude Marchand;Matthias Heinrich;Judith A. Cherni;Elvire A. de la Fresnaye;Lionel Vido;Bernard Multon;Peter K. Kitanidis. Sensitivity Analysis of Photovoltaic Pumping Systems for Domestic Water Supply, *IEEE Transactions on Industry Applications,* **2020,** 56(7), pp.6734-6743.
8. Maddalena,E. T.; Moraes,C. G. S.; Bragança,G.; Junior,L. G.; Godoy R. B.; Pinto,J. O. P.; A battery-less photovoltaic water-pumping system with low decoupling capacitance, *IEEE Transactions on Industry Applications,* **2019,** 55(3), pp. 2263-2271.
9. Elgendy,M. A.; AtkinsonD. J.; Zahawi,B.Experimental investigation of the incremental conductance maximum power point tracking algorithm at high perturbation rates, *IET Renewable Power Generation,* **2016,**10(2), pp. 133-139.

10. Liu, F.; Duan,S.; Liu,F.; Liu B.; Kang,Y.A variable step size INC MPPT method for PV systems, *IEEE Transactions on Industrial Electronics,* **2008**, 55(7), pp. 2622-2628.
11. Mishra, A.K.; Singh, B. An Efficient Control Scheme of Self-Reliant Solar-Powered Water Pumping System Using a Three-Level DC–DC Converter, *IEEE Journal of Emerging and Selected Topics in Power Electronics,* **2020,** 8(4), pp. 3669 - 3681.
12. Derouich, A.; Najib El Ouanjli; Motahhir, S. High-Performance Standalone Photovoltaic Water Pumping System Using Induction Motor, *International Journal of Photoenergy,* **2020,** pp. 1-13.
13. Aboul Zahab,E. E.; Zaki, A. M.; El-sotouhy, M. M. Design and control of a standalone PV water pumping system, *Journal of Electrical Systems and Information Technology,* **2017**, 4(2), pp. 322–337.
14. Sivamani, D.; Ramkumar, R.; Nazar Ali, A,; Shyam, D. Design and implementation of highly efficient UPS charging system with single stage power factor correction using SEPIC converter, *Materials Today: Proceedings,* **2020.**
15. Al-Badi, A.; Yousef, H.; Al Mahmoudi, T.; Al-Shammaki, M.; Al-Abri, M.; Al-Hinai, A. Sizing and modelling of photovoltaic water pumping system, *International Journal of Sustainable Energy*, **2017,** pp.415-427.
16. Singh, B; Shukla, S.; Chandra, A.; Al-Haddad, K. Loss minimization of two stage solar powered speed sensorless vector-controlled induction motor drive for water pumping. IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, **2016.**