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Optimum MPPT Technique for the PV based Field Oriented Control of Induction Motor Feeding Centrifugal Pump

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Abstract

Objectives: To develop and analyze isolated photovoltaic based water pumping system employing Field Oriented Controlled (FOC) three-phase squirrel cage Induction Motor (IM) which in turn is used to run the centrifugal pump. To extract the maximum power from the solar panel during all conditions, Maximum Power Point Tracker (MPPT) has to be implemented. **Method/Analysis:** FOC-IM of 5^{th} order differential equations have been solved using Runga Kutta Method for integration with dq axis in rotor reference frame in MATLAB/Simulink environment. The two MPPT techniques are based on calculations of the instantaneous values of the voltage and current of the PV cell. The Perturb and Observe (P&O) technique is based on the value of perturbation and the Incremental Conductance (INC) technique is implemented using the value of the Incremental Conductance. **Findings:** The power generation from various renewable energy sources is becoming popular because of greater efficiency and depletion of non renewable energy sources. In this paper, an isolated photovoltaic based model is considered which can be suitable for the remote areas where there is no grid connectivity. From the exhaustive study of literature, it is found that very few authors have worked on induction motor and that too employing FOC for PV based model. The characteristics of the Induction Motor are such that it draws high inrush current at starting. The peak power ratings of the inverters and converters depend on this starting current in such finite PV based sources. This ultimately leads to the high cost of the whole system. The analysis to this problem has not been discussed yet, which is an important concern in the field of PV based electric motor drives. This work is incorporated to achieve this objective. **Novelty/Improvement:** The whole developed model is analyzed using the two MPPT techniques viz Incremental Conductance and Perturb and Observe MPPT. The problem of starting current in the motor and the distortions in the torque deviations are highly dependent on the choice of MPPT. So keeping in view of the above two problems, the optimum MPPT technique has been stated in this work.

Keywords: Centrifugal Pump, Field Oriented Control (FOC), Incremental Conductance (INC), Induction Motor (IM), Maximum Power Point Technique (MPPT), Photovoltaic System (PV), Perturb and Observe (P&O)

1. Introduction

In the recent years photovoltaic is gaining importance[1]. They are widely used in various applications in island and remote areas where there is sufficient supply of solar energy and where the availability of electricity through grid connectivity technology has not developed so far[2–4]. Thus water pumping is one of the most satisfying applications of PV system[5]. There are numerous advantages of using PV system as they are renewable, inexhaustible, pollution-free, efficient, maintenance-free and quiet. These advantages of solar energy overpower it among all other renewable energy sources. The output of PV panels varies according to the load. For achieving maximum efficiency it is required the PV panel to operate at its maximum point[6]. Thus various techniques are implemented for maximum power point extraction which has numerous advantages and disadvantages. A look up table

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on a microcomputer was used in[7] which is based on the implementation of database that includes parameters and data. Mathematical equations were used in[8] to model the non linear characteristics of PV generator based on curve fitting method. But the above said two techniques require large memory capacity for data storage and calculations. Open circuit voltage method was used in[6] and in[10] short circuit current method was used by authors. Both these methods are simple but they do not adjust according to the changes in environmental conditions. There are various important advantages of incremental conductance method which is dependent on the derivative of voltage and current. Advantages include: Robustness, simplicity, high accuracy and less time consuming[11].

The type of motor to be used and its control technique has always been the most burning issue of research among the various researchers[12]. The author has used the Permanent Magnet Synchronous Machine using Space Vector Modulation Control Technique[13]. But in this method the current component of torque of PMSM does not change while the component that produces magnetic flux changes and the efficiency of PMSM is low at very slow speeds. Permanent DC motors employing pulse width modulation technique was used by the author[14]. The various disadvantages of using DC motor includes: maintenance and sparking problems. In[15] the Brushless DC motor (BLDC) with direct torque control was used by the author. But the main disadvantage in this approach was sufficient information about the characteristics of the BLDC motor is required to reduce the torque ripple. The author implemented the directly coupled PV system in[16] using Switched Reluctance Motor. It has an advantage of high torque to inertia ratio but it suffers from the disadvantage of maintenance problem and sparking at commutator. The above mentioned problems can be overcome by applying Field Oriented Control on Induction Motor with proportional integral controllers[17]. With this technique, the control of induction motor can be very similarly related to the control of DC motors. In this control, the current component is disintegrated into two components that are flux and torque producing component. The flux component is along the magnetic flux linkage vector and the torque component is at 90 degree to the flux component thus decoupling the torque and flux control[18]. The layout of this work can be given as: - Section 1 details the Introduction followed by Section 2 which explains the Proposed Model and going further Section 3 depicts the Results and Discussion and at last Section 4 describes the Conclusion.

This work presents the proposed FOC-IM structure of water pumping system based on photovoltaic energy. To maximize the generation of photovoltaic energy MPPT is also integrated. The induction motor is driven in the rotor reference frame[19]. The comparison of the two MPPT techniques that is INC and P&O is done. The studied system is modeled and simulated in the MATLAB Simulink environment.

2. System Modeling

The water pumping system requires models of the following 1. Solar panel; 2. MPPT control techniques; 3. Field Oriented Control; and 4. Centrifugal pump.

2.1 Modeling of Solar Panel

The performance and operation of photovoltaic system can be modeled with the help of various mathematical models[20]. The output characteristics curve of the solar cell depends on the variation of temperature (t) and solar radiation (s)[21].

The electrical characteristic of PV cell is given in the terms of output current and output voltage ($\mathbf{V_s}$ $\mathbf{V_s}$):

$$I_{pv} = I - I_1\left[e^{\left(\frac{q(V+IR_s)}{AkT}\right)} - 1\right] - \left(\frac{V_s + R_s I}{R_p}\right) \qquad (1)$$

In the above equation,

I = current at output of PV cell (A).

I_{pv} = current of the incident photon of sunlight (A).

I_1 = saturation current of the diode (A).

q = electron's charge $(= 1.6 \times 10^{-19})$ (C).

V = output voltage of PV cell (V).

k = Boltzmann constant $(= 1.381 \times 10^{-23})$ (J/K).

T = temperature in Kelvin (K).

R_s = resistance that accounts for the losses caused by internal resistance and contacts.

R_p = parallel resistance due to shading losses in PV cells.

A = ideality factor.

2.2 Modeling of Incremental Conductance MPPT

In this method, to determine the effect of change in voltage, incremental changes are measured in PV current and voltage. It can be implemented as follows:-

$$Power\ (p) = Vs * Is \tag{2}$$

$$\frac{dp}{dVs} = Is + Vs\frac{dIs}{dVs} \tag{3}$$

At MPPT

$$\frac{dp}{dVs} = 0 \tag{4}$$

$$I_s + V_s\frac{dI_s}{dV_s} = 0 \tag{5}$$

$$\frac{dI_s}{dV_s} = -\frac{I_s}{V_s} \tag{6}$$

Where

$\frac{dI_s}{dV_s}$ Is the incremental conductance

In contrast to perturb and observe method this method is more reliable as it is strong computationally[22].

2.3 Modeling of Perturb and Observe MPPT

In this system, the system is perturbed for a while and then the power is measured before and after each perturbation. Then this algorithm will perturb the system in the similar direction if there is increase in power, otherwise it will perturb the system in opposite direction if the power decreases[23,24].

2.4 Modeling of Field Oriented Control

This control is a varying frequency control method which is based on the disintegration of stator currents of three phase induction motor into two orthogonal vector components. The motor's magnetic flux is defined by one component and torque by the other. From the references of flux and torque as indicated by the speed control of drive the control strategy calculates the required current components. Usually PI controllers are used to maintain the calculated values of the components of the current close to their recommended values.

Consider the d-q axis model of induction machine in the reference frame which is rotating at synchronous speed ω_s [*Appendix*-A].

$$V_{qsa} = R_{sa}i_{qsa} + \rho\psi_{qsa} + \omega_s\psi_{dsa} \tag{7}$$

$$V_{dsa} = R_{sa}i_{dsa} + \rho\psi_{dsa} - \omega_s\psi_{qsa} \tag{8}$$

$$V_{qra} = R_{ra}i_{qra} + \rho\psi_{qra} + (\omega_s - \omega_{ra})\psi_{dra} \tag{9}$$

$$V_{dra} = R_{ra}i_{dra} + \rho\psi_{dra} - (\omega_s - \omega_{ra})\psi_{qra} \tag{10}$$

The electromagnetic torque developed by the motor is stated below:-

$$T_{em} = 1.5\rho\frac{L_{ma}}{L_{ra}}(\psi_{dra}i_{qsa} - \psi_{qra}i_{dsa}) \tag{11}$$

Where $\mathbf{V_{qsa}}$ and V_{dsa} is the stator q axis and d axis voltage resp, $\mathbf{R_{sa}}$ and R_{ra} is the stator and rotor resistance resp, $\mathbf{i_{qsa}}$ and i_{dsa} is the stator current of q axis and d axis resp, $\psi_{\mathbf{qsa}}$ and ψ_{dsa} is the stator flux linkage of q axis and d axis resp, i_{qra} and i_{dra} is the rotor current of q axis and d axis resp, $\psi_{\mathbf{qra}}$ and ψ_{dra} is the rotor flux linkage of q axis and d axis resp, ω_{ra} is the rotor speed, T_{em} is the electromagnetic torque, L_{ma} and L_{ra} is the magnetising inductance and rotor inductance resp, ρ is the differential operator, V_{dra} and V_{qra} is the rotor d axis and q axis voltage respectively.

Where,

$$\psi_{qsa} = L_{sa}i_{qsa} + L_{ma}i_{qra} \tag{12}$$

$$\psi_{dsa} = L_{sa}\ i_{dsa} + L_{ma}i_{dra} \tag{13}$$

$$\psi_{qra} = L_{ra}i_{qra} + L_{ma}i_{qsa} \tag{14}$$

$$\psi_{dra} = L_{ra}i_{dra} + L_{ma}i_{dsa} \tag{15}$$

Where $\mathbf{L_{sa}}$ is the stator inductance.

The FOC states that the i_{dsa} component of stator current would be aligned with the rotor field and the i_{qsa} component would be orthogonal to i_{dsa}. This can be achieved by selecting ω_s to be the rotor flux's speed and locking the phase of the reference frame system such that the rotor flux is aligned precisely with the d-axis, resulting in

$$\psi_{qra} = 0\ implies\ that\ \rho\psi_{qra} = 0 \tag{16}$$

with

$$\psi_{dra} = \psi_{qra} \tag{17}$$

Which refers that

$$\omega_{sla} = (\omega_s - \omega_{ra}) = \left(\frac{L_{ma}R_{ra}}{\psi_{ra}L_{ra}}\right)i_{qsa} \tag{18}$$

$$T_{em} = 1.5\rho\frac{L_{ma}}{L_{ra}}(\psi_{ra}i_{qsa}) \tag{19}$$

The interaction between the electromagnetic torque (T_{em}) developed and the load torque (T_{load}) is given by the following equation:-

$$T_{em} - T_{load} = j\frac{d\omega_r}{dt} \quad (20)$$

Where j is the moment of inertia of the motor.

It also follows that

$$\rho\psi_{ra} = -\left(\frac{R_{ra}}{L_{ra}}\right)\psi_{ra} + \left(\frac{L_{ma}R_{ra}}{L_{ra}}\right)i_{dsa} \quad (21)$$

There is direct relation between the electric torque and the i_{qsa} component of the stator current and the first order linear transfer function whose time constant is given by $\frac{L_{ra}}{R_{ra}}$ specifies the relationship between the flux ψ_{ra} and the i_{dsa} component of the current.

2.5 Modeling of Centrifugal Pump

The characteristics of the centrifugal pump in terms of flow-head[7] are as follows:

$$H = c_0\omega_r^2 + c_1\omega_r Q + c_2 Q^2 \quad (22)$$

Where ω_r is the speed of the rotor and c_0, c_1, c_2 (Appendix B) are the constants and Q is the flow rate in $\frac{m^3}{\sec}$.

The performance of the pump is determined by plotting a load curve; the $\mathbf{Q - H}$ characteristic of the pipe is given as

$$H = H_h + \mu Q^2 \quad (23)$$

Where H_h is the geometrical height and μ is a constant which is dependent on the parameters of the pipe network that is its conduit diameter and frictional losses.

The load torque of the centrifugal pump $\mathbf{T_{load}}$ varies in direct proportion to square of the speed of the rotor:

$$T_{load} = D_1\omega^2 \quad (24)$$

Where D_1 is the constant and is given as:-

$$D_1 = \rho 2\pi a_1 r_1^2 g\gamma_1\left(r_2^2 - \frac{r_1^2 a_1 g\gamma_1}{a_2 g\gamma_2}\right) \quad (25)$$

Where,

ρ is density of water

a_1 = Impeller blade's height at its input = 5.4 mm

r_1 = Impeller's radius at inlet = 16.75 mm

g = Acceleration due to gravity = $\frac{0.98m}{s^2}$

γ_1 = Impeller blade's angle of inclination at its input = 38°

r_2 = Impeller's radius at its output = 80 mm

a_2 = Impeller blade's height at its output = 2.2 mm

γ_2 = Impeller blade's inclination angle at its output = 33°

3. System Description and Validation

The studies are conducted on 3 hp squirrel cage Induction Motor running at 1750 rpm which is fed by three phase 230 V AC supply. The detailed information about the ratings of the motor is given in Appendix. The block diagram of the developed model is shown in Figure 1.

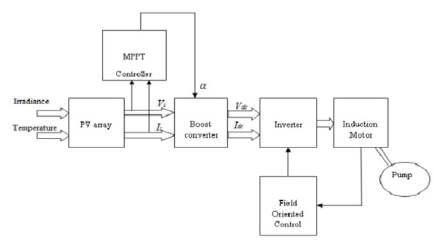


Figure 1. Simulink/MATLAB based diagram of the photovoltaic pumping system fed by field oriented controlled induction motor.

This thesis proposes to design a PV-inverter system feeding an induction motor load which is controlled by Field oriented control.

In this model PV cell operates at various irradiance and temperature conditions according to the weather conditions. The output of the PV cell is variable DC. So to control the output power the MPPT technique is used which computes the current and voltage generated from the PV cell and accordingly gives the gate pulses to the boost converter. This boost converter makes the DC voltage constant which is then fed to inverter to convert it into AC signal. Then the voltage is fed to the FOC controlled induction motor used to drive a pumping system. The two MPPT techniques that are INC and P&O are implemented on the model one by one and the performance of the motor in terms of various parameters like stator current, rotor speed, torque deviation, DC bus voltage and the flow rate of the centrifugal pump is analyzed.

4. Results and Discussions

Various results which have been obtained by the MATLAB Simulations are described below in detailed manner.

The Figure 2 depicts the variation of stator current in both the techniques and it is seen that in starting the overshoot of current is more in case of P&O as compared to INC. This huge excursion in stator current is undesirable as it leads to requirement of peak converter and inverter of high ratings and thus increases cost of AC drives which will reduce the competitive value of AC drives despite its various advantages.

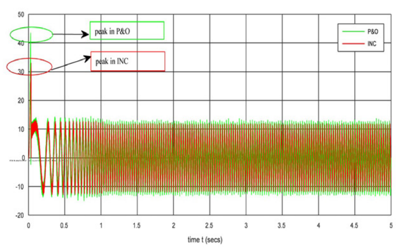
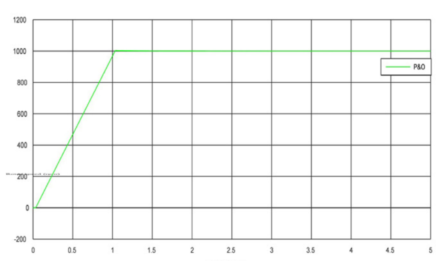


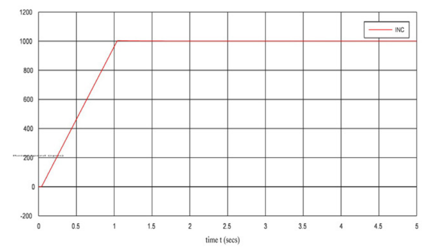
Figure 2. Variation of stator current versus time in INC and P&O techniques.



(a)

As seen from the Figure 3(a) and 3(b) the rotor speed in both the techniques follow the same pattern that is it becomes steady at its maximum value at 0.8 secs.

The Figure 4 clearly depicts the variation of deviation in electromagnetic torque in both the techniques and it shows that the distortion in torque in P&O technique is very high as compared to INC and moreover the torque is more stable in INC versus P&O.



(b)

Figure 3. (a) Variation of Rotor speed versus time in P&O technique. (b) Variation of rotor speed versus time in INC technique.

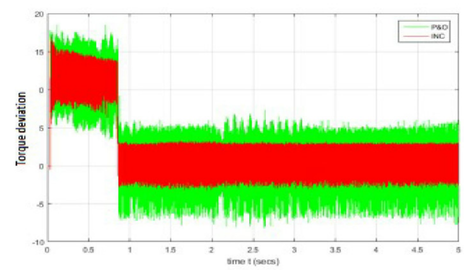


Figure 4. Variation of torque deviation versus time in INC and P&O technique.

The Figure 5 depicts the difference between the DC bus voltages in both the cases. It clearly specifies that the DC bus voltage is more constant and steady in INC as compared to P&O.

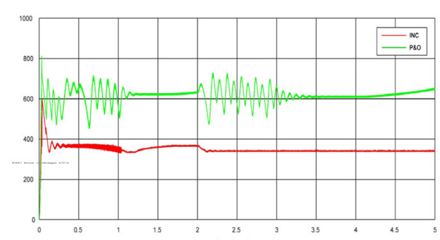
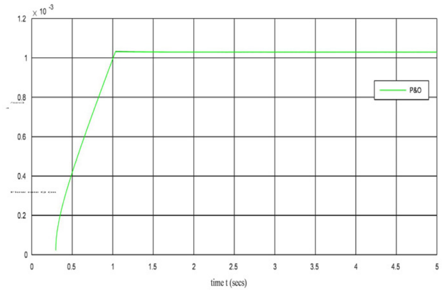


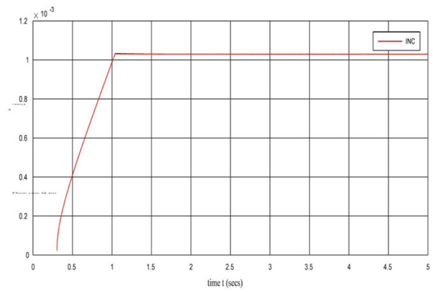
Figure 5. Variation of DC Bus voltage versus time in INC and P&O technique.

In Figure 6(a) and 6(b) the flow rate of pump is described. It can be concluded from the figures that in both cases the flow rate achieves its steady value at same instant but the distortions are present in steady state in P&O and more smooth results are obtained in INC technique.

In the Figures 7(a) and 7(b) the total harmonic Distortions in stator current in both techniques is

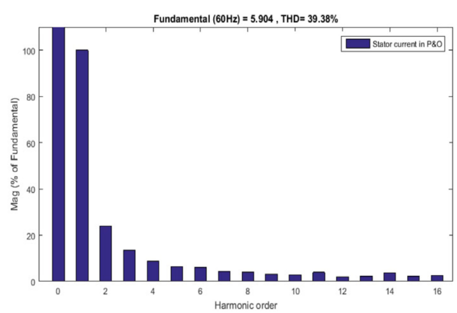


(a)

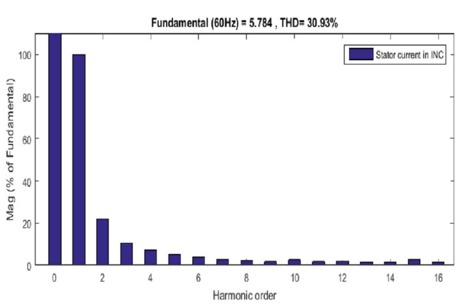


(b)

Figure 6. (a) Flow rate versus time in P&O technique. (b) Flow rate versus time in INC technique.



(a)



(b)

Figure 7. (a) Total harmonic distortion in stator current in P&O technique. (b) Total harmonic distortion in stator current in INC technique.

depicted. It shows that its value is 39.38% in P&O and 30.93% in INC.

The values of THD in both the cases is shown in Table 1 form.

Table 1. Total harmonic distortion in both the cases

Techniques Parameters	INC	P&O
Stator current	30.93%	39.38%

5. Conclusion

In this research work the performance of the Field Oriented Control of an Induction motor that is directly feeding the centrifugal pump based on photovoltaic system has been analyzed. The two MPPT techniques are successfully implemented on this system that is INC and P&O and by conducting the comparative analysis through simulation results as obtained in the MATLAB, it is observed that the operation of the motor during INC is showing better results as compared to P&O. The difference can be seen more clearly in case of stator current and electromagnetic torque of an induction motor. By incorporating the INC technique the overshoot in stator current during starting can be minimized and thus reduces the cost of the system. Hence huge excursion in stator current is undesirable, as it leads to requirement of peak converter and inverter of high ratings and thus increases cost of AC drives which will reduce the competitive value of AC drives despite its various advantages. The distortions in torque deviation can also be reduced by employing INC technique.

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7. Appendix

The Induction Motor used in this model for comparing the two MPPT techniques is of 3hp three phase squirrel cage Induction Motor running at 1750 rpm.

The values of the various parameters of the Induction Motor are listed below:

Power,	=	3 hp
Voltage,	=	220 V (rms)
Frequency,	=	60 Hz
Stator Resistance (R_s),	=	0.435 ohm
Rotor Resistance (R_r),	=	0.816 ohm
Leakage Inductance of Stator,	=	0.002 H
Leakage Inductance of rotor,	=	0.002 H
Mutual Inductance,	=	$69.31*10^{-3}$ H
Inertia,	=	0.089 kg*m^2

The centrifugal pump used in this thesis is of following dimensions:

Geometrical Head (H_h),	=	0.1 m
c_0,	=	$1.61*10^{-4}$ ms^2rd^{-2}
c_1,	=	$2.584*10^{-3}$ $ms^2l^{-1}rd^{-1}$
μ,	=	0.98388 msl^{-1}

The solar panel used in the model is of module Stion STN-110 in which the panel of solar array consists of 8 parallel strings and 5 series connected modules per string.

The list of various parameters is detailed below:

Maximum Power = 110.625 W

Open Circuit Voltage (V_{oc}) = 51 V

Voltage at Maximum Power Point (V_{mpp}) = 37.5 V

Temperature coefficient of V_{oc} = -0.316 %/deg.C

Cells per Module = 100

Short- Circuit Current (I_{sc}) = 3.37 A

Current at Maximum Power Point (I_{mpp}) = 2.95 A

Temperature Coefficient of I_{sc} = 0.00029674 %/deg.C

Light generated Current (I_l) = 3.4128A

Diode Saturation Current (I_0) = 1.9862e^{-11} A

Diode Ideality Factor = 0.77016

Shunt Resistance (R_{sh}) = 160.2582 ohms

Series Resistance (R_s) = 2.685 ohms