An Analytical Research on Optimization of the Photovoltaic Pumping System Control

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Abstract-
The objective of this study is to investigate a three-phase induction motor (IM) based photovoltaic solar water pumping system (PVWPS) that has cheap cost, good performance, and doesn't require chemical energy storage. There are two main controllers in the PVWPS control scheme. The first controller uses a strong MPPT control strategy based on the Kalman filter algorithm (KF-MPPT) to regulate the system to attain its maximum. Conversely, the second controller uses Direct Torque Control (DTC) with a 12-second timer. This method involves using a three-level inverter with a neutral point clamped (NPC) arrangement to regulate the IM using a centrifugal pump. Additionally, by raising the torque and flux hysteresis regulator levels to three and five levels, respectively, the suggested control's performance is improved without compromising the efficiency of the system. The entire system was constructed and simulated in the MATLAB/Simulink environment to observe the behaviors of the PVWPS with the suggested control. A comparison study is also included in this paper to demonstrate how well the suggested control performs in contrast to the traditional controls. Using varying radiation, the performance of the KF-MPPT, VSS-P&O-MPPT, and VSS-INC-MPPT is first compared. Next, the suggested KF-MPPT-PDTC and the traditional KF-MPPT-DTC are compared under a daily climatic profile.

Keywords— *Chemical Energy Storage, Water Pumping System (PVWPS), Direct Torque Control (DTC), Kalman Filter Algorithm (KF-MPPT).*
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INTRODUCTION

Because of the harm that fossil fuels cause to the environment. It has been said that clean energy derived from natural sources is renewable energy. Solar energy has drawn the most attention among renewable energy sources because of its many benefits. In many applications, particularly in the photovoltaic water pumping system, it is quickly becoming mainstream and competitive with traditional energy sources. A viable replacement for traditional diesel-powered pumping systems is water pumping based on photovoltaic technology.

PV systems that are freestanding fall into two categories. The first one uses the storage battery to store the excess electricity generated by the PV system, while the second one uses a tank to store the pumped water. Using battery storage in a photovoltaic solar water pumping system may increase the PV system cost by 10–50% and affect the lifetime of the system. As a result, the implementation of a photovoltaic solar water pumping system without a storage battery increased, especially in rural areas where grid connectivity is unavailable. PV is considered an essential part of the photovoltaic solar water pumping system (PVWPS). The efficiency of the PV array of the photo- voltaic solar water pumping system may be affected by two factors: the variation of the irradiations and temperature and the nature of the load. These problems can be solved using maximum power point tracking (MPPT) techniques which are responsible to extract the optimal power from the PV array, whatever the climatic conditions. Many types of MPPT have developed in the literature, each has pros and cons. The Conventional methods perturb and observe (P&O) and incremental conductance (INC) are the most widely used because of their simple implementation. Nevertheless, these methods give high oscillation, and the performance reduces when tracking the maximum power due to the fixed-step tracking. Therefore, variable step sizes are used, which are automatically adjusted according to the operating point to overcome the weakness of the step fixed. However, those algorithms have difficulty with the initial step-change in the duty cycle under rapid environmental changes. Therefore, several researchers have worked on soft computing and intelligent methods such as the Kalman filter, fuzzy logic control (FLC), artificial neural network (ANN), partial swarm optimization (PSO), ant colony optimization (ACO), and artificial bee colony (ABC). These algorithms give a fast response when they are tracking the maximum power. Among these methods, the most popular one is the Kalman filter, which provides an efficient recursive filter based on the estimations of past, present, or even future states and noisy measurements. The choice of motor in PVWPS depends on efficiency, availability, cost, and reliability. Therefore, many types of motors have been studied. Each one has its own advantages and disadvantages. Researchers have worked with DC motors due to their simplicity. However, the problem is that these motors need regular maintenance due to the commutators and brushes to overcome these drawbacks. A brushless permanent magnet motor (BLDC) has been proposed, it has a more straightforward (brushless) mechanical design. However, these motors' disadvantage is that they are recommended only for low-power PV systems. Therefore, other researchers have studied photovoltaic pumping systems based on AC motors, such as permanent magnet synchronous motors (PMSMs) and induction motors (IMs). However, IM has succeeded in outperforming PMSM due to its reliability and lack of need for permanent maintenance. In addition, due to the low cost of this kind of motors, developing countries prefer using it for solar water pumping applications. Nevertheless, this type of motor has a coupling effect between torque and flux, making it relatively complex. Therefore, a field-oriented control (FOC) strategy has been proposed to control the torque and flux of the IM independently as the DC motor. However, this technique is influenced by parameter changes in the IM and external load disorders. To overcome these difficulties, direct torque control (DTC) has been proposed by Takahashi and Noguchi. This technique has good robustness under IM parameter changes, does not require existing regulating loops, and it is easy to implement. However, this control uses a hysteresis controller, which generates high ripples in torque and flux primarily at low speed, producing more noise, mechanical vibration, and a higher switching frequency variation that increases the total harmonic distortion (THD) of the stator current. Researchers proposed numerous strategies to enhance the dynamic performance of the DTC control by minimizing the torque and flux ripples and keeping the frequency at a constant value, as well as reducing the THD of stator current. In the authors developed the DTC using space vector modulation (SVM). This technique requires accurate PI controller design and system parameters. Others researchers worked on the fuzzy logic controller and artificial neural network. These techniques produce good results. However, the problem is that the practical implementation of these methods is very complicated, and their algorithms need a long computational time.

DESCRIPTION AND MODELLING OF THE SYSTEM

The schematic diagram of the system analyzed in this paper is shown in Fig. 1. It consists of a photovoltaic array, a boost chopper working as a Maximum Power Point Tracker (MPPT), a current source inverter and a three-phase squirrel cage induction motor driving a mono-cellular centrifugal pump. In addition, a discrete linear quadratic regulator with integral action is incorporated to eliminate the static error in steady state.

(i) Photovoltaic array model- Photovoltaic generators are neither constant voltage sources nor current sources but can be approximated as current generators with dependant voltage sources. The array considered in this study is a 16 series connected modules type AEG.40 where the I–V characteristic can be expressed as an implicit equation (Betka et al., 2004): The I–V curve is essentially influenced by the variation of two inputs: the solar insolation and the array temperature. The adaptation of Eq. (1) for different levels of solar insolation and temperature can be handled by the following equations (Betka, 2005; Bione et al., 2004):

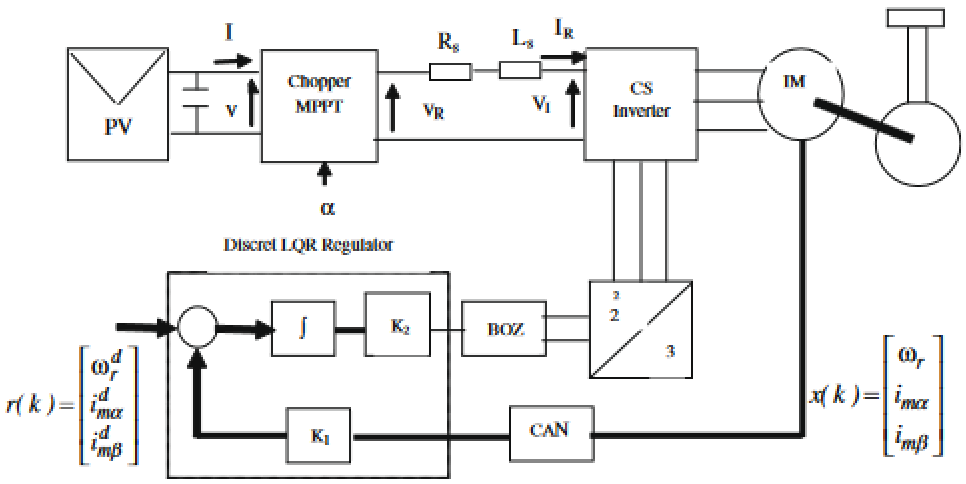


Figure 1- Overall control PV pumping system

(ii) Current source inverter model- The current source inverter presents to the motor phase currents which are rectangular in nature and 'on' for only 120° of each half cycle. Assuming that the smoothing inductor is large and the commutation periods are negligible, the d and q axis currents are expressed as (Olorunfemi,1991):

$$I_{pv} = I_{sc} - I_0 \cdot \left(\exp\left(\frac{V + R_s \cdot I}{V_{th}} \right) - 1 \right) \tag{1}$$

$$\Delta T = T - T_r \tag{2}$$

$$\Delta I = \alpha \left(\frac{E}{E_r} \right) \Delta T + \left(\frac{E}{E_r} - 1 \right) I_{sc} \tag{3}$$

$$\Delta V = -\beta \Delta T - R_s \Delta I \tag{4}$$

$$V = V_r + \Delta V \tag{5}$$

$$I = I_r + \Delta I \tag{6}$$

$$\dot{X} = F(X, U) \tag{7}$$

where

$$\frac{d\omega}{dt} = -\frac{f}{J}\omega + \frac{3}{2}p\frac{M}{J} i_{md} i_{qs} - \frac{3}{2}p\frac{M}{J} i_{mq} i_{ds} - \frac{1}{J}T_L \tag{8}$$

$$\frac{di_{md}}{dt} = -\frac{r_2}{L_r} i_{md} + (\omega_1 - \omega) i_{mq} + \frac{r_2 M}{L_r^2} i_{ds} \tag{9}$$

$$\frac{di_{mq}}{dt} = -\frac{r_2}{L_r} i_{mq} - (\omega_1 - \omega) i_{md} + \frac{r_2 M}{L_r^2} i_{qss} \tag{10}$$

where

$$\dot{X} = [\omega \quad i_{md} \quad i_{mq}]^T \quad \text{and} \quad U = [i_{ds} \quad i_{qs} \quad \omega_1]^T$$

(iii) Three phase induction motor model- The state equations of a symmetrical squirrel cage induction motor expressed in the synchronous frame are expressed as non-linear differential equations (Murata,1990):

CONTROL STRATEGIES OF THE PVWPS

(i) Control PWM- The PWM is necessary for controlling two VSI levels of the inverter. This technology compares two signals, a triangular signal of high frequency (fp), called a “carrier”, and a reference signal, called a “modulator”, with a frequency fm<< fp. The comparison between these two signals can generate the pulse required to switch the mode of the inverter. Figure 2 shows a comparison of these two signals, which are responsible for controlling the inverter switches.

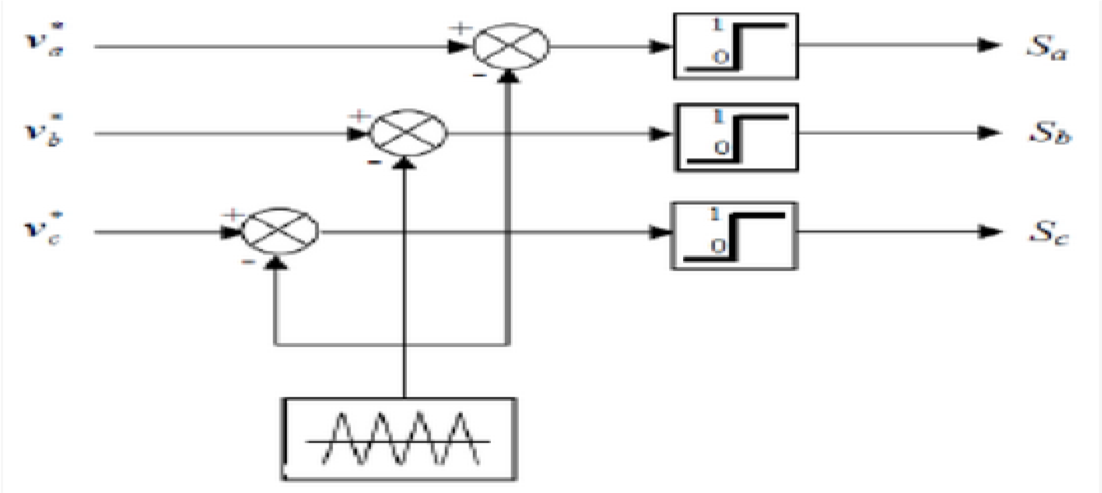


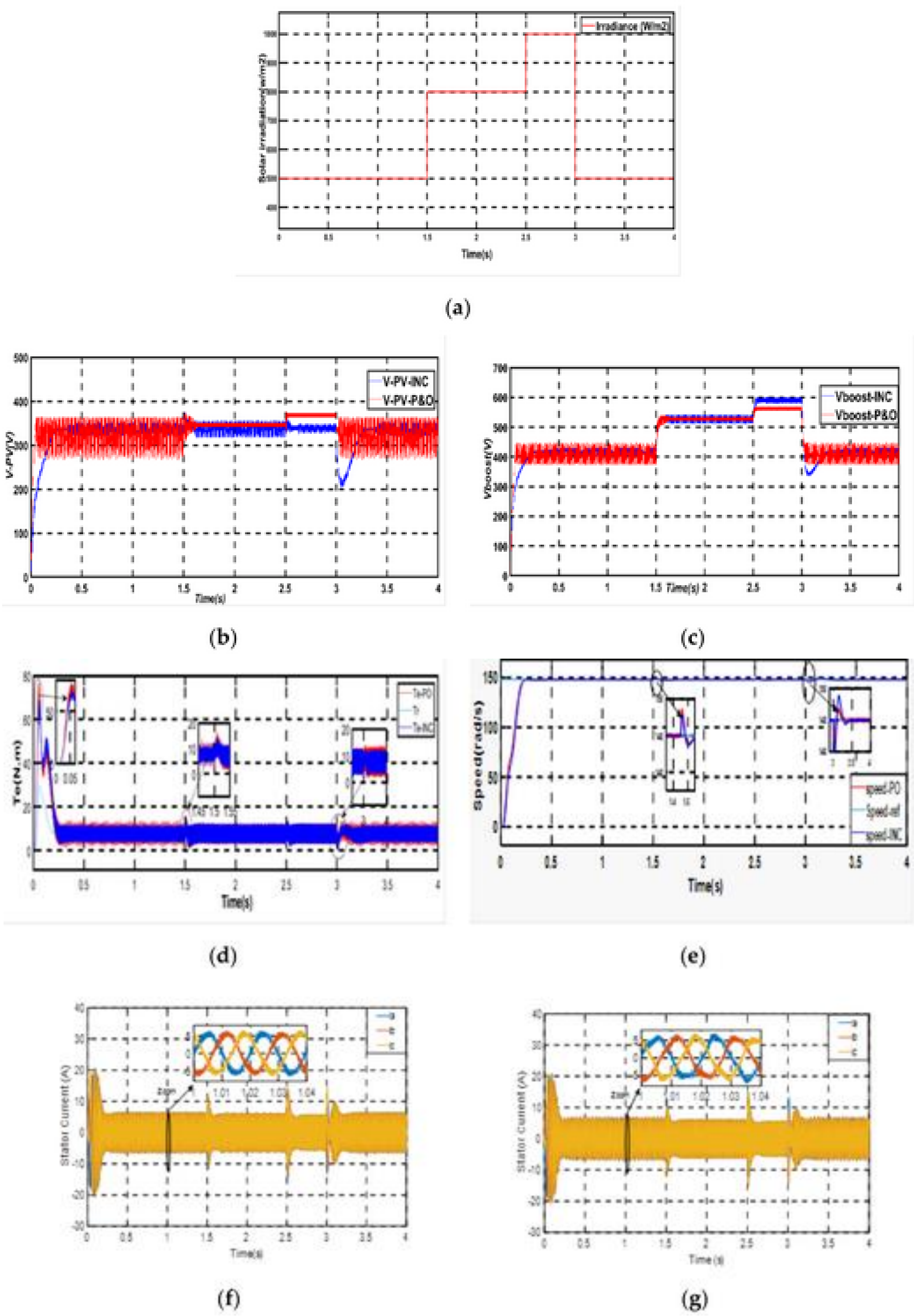
Figure 2- The control of the Inverter switch

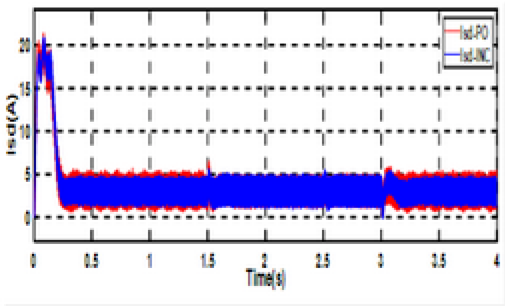
(ii) MPPT Control with variable step Incremental Conductance and Perturb and Observe Algorithms- Several MPPT algorithms have been used in the literature to extract the maximum power from the PV panel with each change in solar irradiance. The most popular of these are perturb and observe and incremental conductance. The purpose of these algorithms is to adjust the duty cycle of a boost converter in such a way that boosted DC voltage can be obtained. "P&O and INC introduce a perturbation (ofs) that has to be either variable or fixed step sizes to reach the maximum power point. Problems may arise with changes in irradiance. With a fixed step size, the oscillation appears to be in a steady-state. However, a variable step size automatically chooses the step sizes, resulting in small oscillations and fast-tracking. In this paper, we used a variable step size for P&O and INC. "

(iii) Field-Oriented Control- The induction motor needs to be driven similarly to a DC motor; of the many available controls, field-oriented control is the most commonly used, and works by decoupling the flow and torque into two orthogonal components. This control consists of two types, DFOC and IFOC, and these have been used in many applications. IFOC control consists of aligning the rotor flux (or stator) to one axis of the park reference.

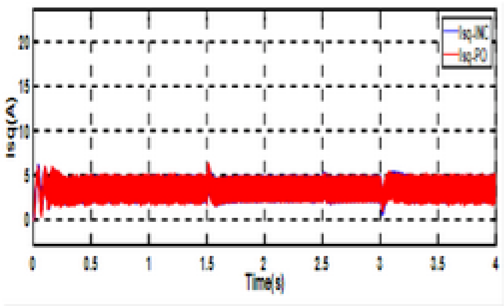
SIMULATION RESULTS

Simulations of the proposed system were performed in Matlab Simulink under different conditions to test the performance of the system, as shown in Figure 3. In the first step, we chose to change the radiation from 500 W/m^2 to 1000 W/m^2, before stabilizing at 500 W/m^2 while maintaining the temperature to test the effect on PV system performance of sudden changes in radiation, as shown in Figure 3a. **Figure 9.** (**a**) Solar radiation. (**b**) Output voltage of the PV. (**c**) Output voltage of the boost converter. (**d**) Torque Evolution (N.m). (**e**) Mechanical Speed (**f**) Stator current P&O. (**g**) Stator current INC. (**h**) Current Isd. (**i**) Current Isq. (**j**) Flow pump evolution (m^3/s). (**k**) Motor output power. (**l**) Output voltage of the PV.

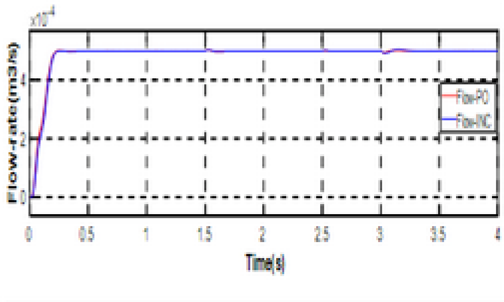

Irradiance (W/m2)
Time(s)
(a)
V-PV-INC
V-PV-P&O
V-PV(V)
Time(s)
(b)
Vboost-INC
Vboost-P&O
Vboost(V)
Time(s)
(c)
Te-PO
Tr
Te-INC
Te(N.m)
Time(s)
(d)
Speed(rad/s)
speed-PO
Speed-ref
speed-INC
Time(s)
(e)
Stator Current (A)
Time(s)
(f)
Stator Current (A)
Time (s)
(g)



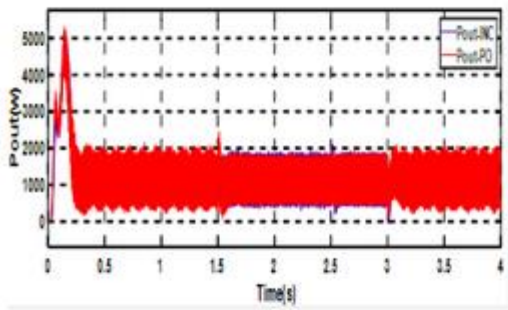
(h)



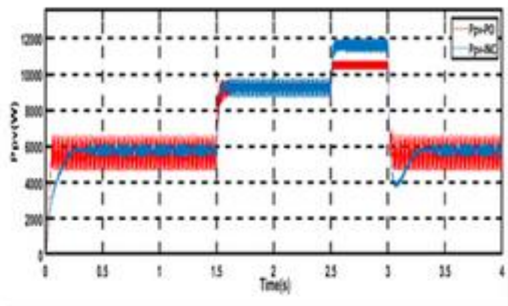
(i)



(j)



(k)



(l)

Figure 3- (a) Solar radiation, (b) Output voltage of the PV, (c) Output voltage of the boost converter, (d) Torque Evolution (N.m), (e) Mechanical Speed (f) Stator current P&O, (g) Stator current INC, (h) Current Isd, (i) Current Isq, (j) Flow pump evolution (m^3/s), (k) Motor output power, (l) Output voltage of the PV.

In the second step, the P&O and INC MPPT techniques were applied to the system one by one, using the variable step which is changed with respect to the maximum power at their location.

In Figure 3c,b, first, it can be observed that rapid changes in atmospheric conditions (increase or decrease) produce a change in the output voltage of the PV, leading to changes in the output of the boost converter. Second, based on a comparison between P&O and INC, it can be seen that both methods of MPPT can achieve MPP tracking, but simulating Vboost at (0 to 0.1 s) and (at 3.05 to 3.5 s) shows better results in INC than in P&O, with less oscillation.

In Figure 3d, the variation in electromagnetic torque when the irradiance changes can be observed. It can be seen that for P&O at (0 to 0.05) and (1.45 to 1.55), the deviation is higher than that for INC, leading to greater torque stability in INC than P&O.

Figure 3e shows the rotor speed variation of the induction motor using the two techniques of MPPT. Good responses in starting performance and steady-state can be observed, with good dynamics and negligible overshoots and without static errors. It can also be seen that the rotor speed follows the reference values and is affected by the increase/decrease of irradiation from (500 W/m^2 to 1000 W/m^2)/(1000 W/m^2 to 500 W/m^2).

Figure 3f,g shows the variation of stator currents with P&O and INC. It can be seen that the stator currents increase with solar radiation; in addition, it can be seen that the peaks in P&O are greater than those in INC, which can affect system requirements by increasing the cost of the inverter and converter.

Figure 3h,i depict the variation in direct current (Isd) and quadratic current (Isq). It can be seen that Isq changes according to torque variation. In contrast, Isd varies according to flux variation, which shows the strength of the indirect field-oriented control with respect to decoupling between torque and flux.

Figure 3j shows the evolution of the flow rate of the pump. It can be seen that both MPPT techniques have the same results, with barely noticeable distortions more in P&O than INC.

Figure 3k,l show the PV power (Ppv) and motor output power (Pout) with variations in solar irradiation, and it can be seen that the power is dependent on the increase or decrease in irradiation; in addition, the comparison between (Ppv) and (Pout), which is Pout = Ppv, shows that losses due to motor efficiency are system losses.

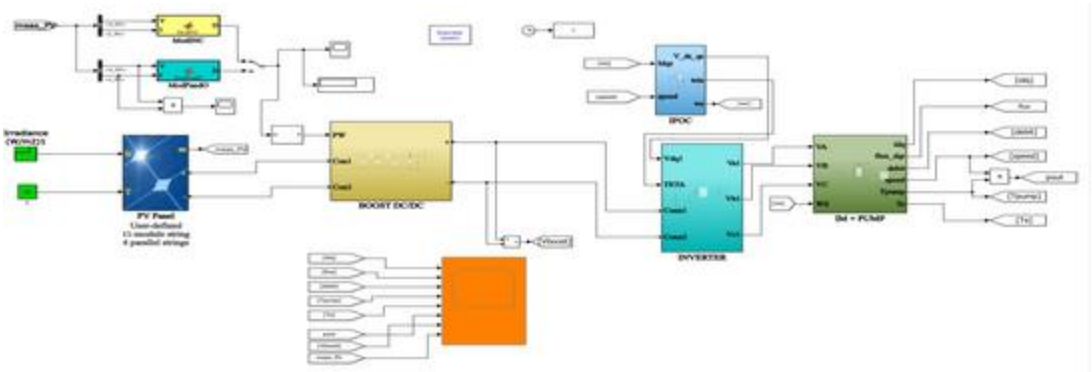


Figure 4- Solar pump simulation design

CONCLUSION

In an effort to find a system with high performance and efficiency, an IM-based photovoltaic water pumping system without battery storage was investigated. In this study, the photovoltaic water pumping system was controlled by three MPP T controls: VSS-P&O, VSS-INC, and KF in conjunction with DTC. The outcomes showed that, in terms of power oscillation and time response, the KF outperforms the VSS-P&O and VSS-INC under rapid irradiation. The chosen photovoltaic water pumping system was then controlled by combining the KF with the suggested DTC, as determined by the results obtained. This method is suggested as a way around the drawbacks of traditional DTC. The results of the simulation shown that the suggested control greatly lowers the torque, flux ripple, and overall harmonic distortion of the stator currents.

The performance of the solar water pump was successfully enhanced in this work. The effectiveness of the system utilizing IFOC was examined based on simulated tests conducted under abrupt changes in climate. A comparison with the application of a variable step was done between INC and P&O. The comparison's findings demonstrated that whereas INC showed less oscillation and performed better with abrupt changes in irradiation, the P&O algorithm displayed oscillations near the ideal value. Furthermore, when it came to the stator current and electromagnetic torque of an induction motor, the motor operating with incremental conductance produced superior simulation results than perturb and observe.

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