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Research Article

A Sensorless MPPT Approach For PV Pump System Used BLDC Motor

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***Abstract*—PV irrigation systems have begun to be used intensively today, as energy needs increase. In Partially Shaded Conditions (PSC), the efficiency of the PV system decreases significantly, and traditional Maximum Power Point Tracking (MPPT) algorithms become insufficient. On the other hand, traditional MPPT algorithms require sensors to measure the current and voltage of the PV system. In this study, a sensorless hybrid MPPT algorithm is proposed to reduce system costs and enable operation without the need for PV system data. A simulation study was conducted in the MATLAB/Simulink environment to examine the PV system. The proposed algorithm has been tested under four different PSC scenarios. PV system power, motor speed, and currents were examined under each condition. The high maximum power tracking performance of the proposed algorithm is demonstrated through simulation results. In the steady state, the lowest MPPT efficiency was 95.66%, whereas the highest MPPT efficiency was 99.9%. The MPPT algorithm completed in less than 2 seconds, with the first stage taking 1.3 seconds to reach most of the maximum PV system power. The second stage of the MPPT algorithm was used to achieve maximum power in a narrower area.**

Index Terms—**PV pump, BLDC, Partial shading, MPPT, Sensorless algorithm.**

I. INTRODUCTION

FOSSIL FUELS, which are used extensively in energy production, are decreasing. At the same time, energy production costs continue to increase. On the other hand, consumption of fossil fuels causes significant environmental problems. For these reasons, interest in renewable energy sources is increasing day by day [1]. Solar energy has an important place among renewable energy sources. Photovoltaic (PV) irrigation systems have been increasing in importance in recent years. It offers an important alternative solution, especially in agricultural irrigation, in places where there is no energy network and energy delivery is costly.

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Many different types of motors are used in photovoltaic irrigation systems, such as synchronous reluctance motor (SynRM), permanent magnet synchronous motor (PMSM), induction motor and brushless direct current motor (BLDC) [2-6]. BLDC motors are used as a better alternative to the induction motor in PV fed water pumping systems. This motor is compact, robust and efficient compared to the AC motor. Additionally, a BLDC motor has many advantages such as reliability, low maintenance, easy to drive and simple control. Therefore, BLDC motors have received increasing attention in water pumping systems in recent years due to their superior features. [7]. DC-DC converters are used in traditional PV pump systems. In [8], the MPPT technique without a DC-DC converter was developed for a PV pump system using a BLDC motor. In [9], a PV irrigation system was created by connecting a PMSM motor directly to the DC line of the inverter. However, DC-DC converters are used in many conventional PV water pump systems with MPPT algorithms.

PV panels operate with very low efficiency. Therefore, various Maximum Power Point Tracking (MPPT) algorithms and methods have been developed to obtain maximum power from PV panels [10, 11]. In the literature, two important atmospheric conditions that are effective in obtaining energy from PV power systems have been examined. These atmospheric conditions are known as uniform solar radiation and partial shading conditions (PSC). Perturb&Observe (P&O), Incremental Conductivity (InC), 0.8VoC and derivatives of these methods are used extensively under uniform radiation conditions [12, 13]. However, to achieve higher efficiency and lower power ripple, optimization-based MPPT algorithms such as artificial intelligence-based [14], Particle Swarm Optimization (PSO) and Gray Wolf Optimization (GWO) have been developed [15, 16]. Today, similar MPPT algorithms continue to be developed.

Conventional algorithms are ineffective in operating under atmospheric conditions under PSC. Because, Local MPP and Global MPP points are created in the system which is operated

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under PSC. The MPPT algorithms need to find the GMPP. This is a complex and quite difficult process. For this purpose, various optimization and artificial intelligence-based MPPT algorithms along with derivatives of conventional MPPT algorithms have been developed. Some of the algorithms that have a lot of space in the literature can be examined as; a hybrid method including the particle swarm optimization (PSO) and search-skip-judge algorithms [17], Asymmetrical interval type-2 fuzzy logic control [18], a dynamic particles MPPT method [19] , MPPT Method Based on Inflection Voltages [20], Deep reinforcement learning approach MPPT [21], Artificial neural network based modified incremental conductance algorithm [22], Variable step size P&O MPPT controller by applying Ɵ modified krill herd algorithm [23], Chaotic Flower Pollination Algorithm (C-FPA) [24], improved sparrow search algorithm (ISSA) [25], Modified Butterfly Optimization Algorithm [26], Improved Team Game Optimization Algorithm [27], Harris hawk optimization (HHO) [28], Manta ray foraging optimization (MRFO) [29], and Salp Swarm Optimization (SSO) [30]. However, the literature is not limited to this algorithms; it is possible to examine many more studies.

Apart from this, scanning-based algorithms, which form the basis of P&O and InC algorithms, also find their place in the literature. The most important feature of these algorithms is their simple structure and applicability. A very recently developed two-level Voltage partitioning method appears to work with high efficiency [31]. Voltage partitioning and scanning techniques are fundamentally very similar. Scanning algorithms are especially concentrated on finding the voltage value at the GMPP point [32-34]. One of the newest of these algorithms is the voltage scanning algorithm and stands out with its high performance [35].

While the radiation value on photovoltaic panels may be uniform, the radiation values falling on each panel may be different due to natural events such as cloud shadowing and different external factors. In this case, each panel produces voltage in relation to the radiation value on itself. As a result, different maximum power points occur under different shading conditions. These points must be determined in order to obtain maximum efficiency from the system.

In recent years, there has been an increase in research into obtaining maximum efficiency from photovoltaic irrigation systems operating under PSC. In these studies, one or more of the current, voltage and speed parameters of the motor side are measured. At the same time, one or more of the current, voltage and radiation values are measured on the PV side [36-38]. Different motor types and MPPT algorithms have been used in PV pump systems operating under PSC. These MPPT algorithms are implemented using analytical or intelligent methods. In these studies, the advantages of BLDC motors such as easy driving technique and simple controllability were utilized [39-42]. Sensors are a significant cost in PV systems. For this reason, research on sensorless MPPT algorithms has recently been concentrated. Generally, algorithms without current sensors come to the fore, because the voltage of the PV system can be measured with simpler and lower-cost methods. In some of these algorithms, the current estimation of the PV system is made by using DC-DC converter and in others by using the load data [43-46].

Obtaining maximum power from a PV system under partial shading conditions generally requires complex and difficult algorithms. This reveals the need for advanced microcontrollers and increases the system cost. Although voltage division algorithms are simple, they require PV panel parameters. Small changes in panel data or uncertain parameters limit system efficiency. The proposed algorithm stands out because it is both simple and does not require panel data, and its application is very simple. On the other hand, measuring current and voltage increases the system cost. Especially at high current values, both installation and sensor costs increase. Since panel currents and voltages are not measured in the proposed algorithm, a more compact structure is achieved and the system cost is reduced.

In this study, a hybrid MPPT algorithm was created by combining the voltage scanning algorithm with a modified P&O algorithm. PV irrigation system consists of ZETA DC-DC converter, BLDC motor and PV panels. In this algorithm, the back EMF and mechanical power of the motor are approximately calculated by using the speed and current information of the motor. The back EMF of the motor was scanned and mechanical power was approximately obtained. The maximum power value obtained from the scan is not accurate and has determined the area of maximum power. The data in the first stage formed the input data of the MPPT algorithm in the second stage. The second step used the motor speed and current information and determined the exact value of the maximum power point in the MPP region obtained in the first step. The most important advantage of this method is that only motor data is used. None of the current, voltage and radiation values of the PV system were used. Thus, the overall cost of the system is reduced. On the other hand, there are no complex operations in the algorithm. Implementation of the algorithm can be easily done.

II. PV PUMP SYSTEM MODELING

A. PV System

Figure 1 shows a PV cell model consisting of a well-known diode, a current source, and 2 resistors. The output current produced here is expressed as seen in the equations between equation 1 and equation 3.

$$I = I_{PV} - I_D - I_{R_P} \tag{1}$$

$$I = I_{PV} - I_0 \left[exp\left(\frac{V+R_S I}{a}\right) - 1 \right] - \frac{V+R_S I}{R_P} \tag{2}$$

$$a = \frac{N_s nkT}{q} \tag{3}$$

where I_0 refers to the reverse saturation current or leakage current of the diode. a is the ideality factor, N_s is the number of series-connected cells, n is the diode ideality constant, k is the Boltzmann constant (1.3806503x10-23 J/K), T is the cell temperature (Kelvin), and q is the electron charge (1.60217646x10-19 C). The current generated by the PV cell by the effect of light is present in Equation 4.

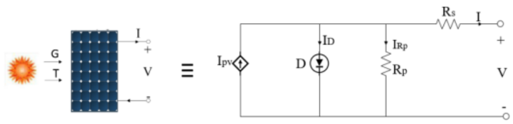

Fig.1. Electrical equivalent circuit model of a PV cell

$$I_{PV} = \left(I_{PV,n} + K_I(T - T_n)\right)\frac{G}{G_n} \quad (4)$$

where $I_{PV,n}$ refers to the current generated for 25 °C and 1000 W/m^2, T_n refers to the nominal temperature (Kelvin), G refers to the radiation value on the panel surface (W/m^2), and G_n refers to the nominal radiation value (W/m^2). The saturation current of the diode (I_0) is given in Equation 5.

$$I_0 = \frac{I_{SC,n}+K_I(T-T_n)}{\exp\left(\frac{V_{OC,n}+K_V(T-T_n)}{a}\right)-1} \quad (5)$$

where $I_{SC,n}$ is the nominal short-circuit current, $V_{OC,n}$ is the nominal open-circuit voltage, K_I is current coefficient, and K_V is voltage coefficient. If the radiation value on each panel in a PV array is the same, it is in uniform radiation. However, if the radiation values on the panels are different, partial shading conditions occur. While only one maximum power point occurs in uniform insolation, more than one maximum power point will occur in operation under PSC. Some of these points are LMPP and one of them is GMPP. In this study, the P-V graph formed in the case of uniform radiation and PSC is seen in Figure 2. The PV system consists of six series connected panels. The voltage produced by a panel at its maximum power point is 35.3V, its current is 4.39A and its power is 154.967W. Accordingly, the maximum power that the PV system can produce is given as 929.8W.

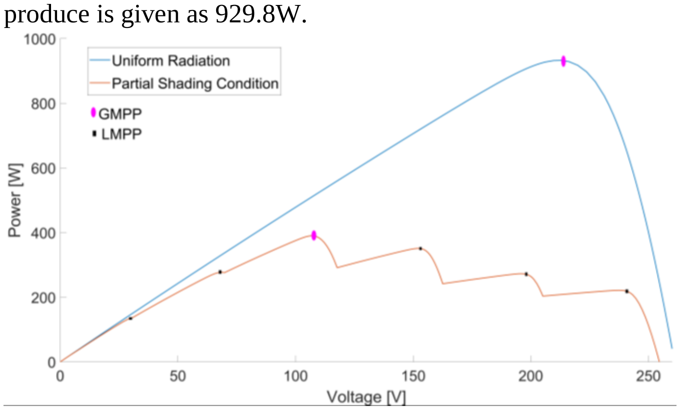

Fig.2. Uniform Radiation and P-V graph formed in case of PSC

B. DC-DC converter

The first stage is a DC-DC converter which used to operate the PV irrigation system at maximum power point. In this study, the zeta converter, which is widely used in PV systems, was used as the DC-DC converter. Zeta converter is a fourth order DC-DC converter that operates by increasing or decreasing the input voltage. The Zeta converter consists of components such as input inductor L_1, output inductor L_2 and intermediate capacitor C_1. Duty cycle D is estimated with the equation given in Equation 6.

$$D = \frac{V_{dc}}{V_{dc}+V_{mpp}} \quad (6)$$

$$I_{dc} = \frac{P_{mpp}}{V_{dc}} \quad (7)$$

$$L_1 = \frac{DV_{mpp}}{f_{sw}\Delta I_{L1}} \quad (8)$$

$$L_2 = \frac{(1-D)V_{dc}}{f_{sw}\Delta V_{C1}} \quad (9)$$

$$C_1 = \frac{DI_{dc}}{f_{sw}\Delta V_{C1}} \quad (10)$$

where V_{dc} is the average value of the output voltage of the Zeta converter. The estimate of the average current I_{dc} flowing through the inverter is given in equation 7. After D and I_{dc} estimation L_1,L_2 and C_1 estimation are given between equations 8 and 10.

C. BLDC motor

BLDC motors are widely used due to their long life, ability to operate at high speeds, high moment and high efficiency. There is a three-phase winding on the stator of the BLDC motor. There are permanent magnets in its rotor. Motor windings are energized with a three-phase inverter. Six-step switching is used as the switching technique. When the six-step switching technique is applied to the windings, two phase windings will be energized at any time. According to the results obtained in this case, the mathematical equations of the BLDC motor using the six-step switching technique are similar to the conventional DC motor. BLDC motor shows approximately DC motor characteristics. Accordingly, the mechanical power of the motor Pmech and the power Pdc at the output of the DC-DC converter can be approximately equal when losses of motor, pump and inverter are ignored. The mechanical power of the motor is given in Equation 11. Where, Ia indicates the current of the motor and is approximately the same as Idc calculated in Equation 12. DC link power is calculated in Equation 13. where, Vdc shows the DC link voltage of the inverter.

$$P_{mech=}E_z.I_a \quad (11)$$

$$I_{dc} = \frac{I_{a\_ph}+I_{b\_ph}+I_{c\_ph}}{2} \quad (12)$$

$$P_{dc=}V_{dc}.I_{dc} \quad (13)$$

$$E_z.I_a \cong V_{dc}.I_{dc} \quad (14)$$

$$E_z = k.\omega \quad (15)$$

According to equation 14 it can be $I_{dc} \cong I_a$. If the speed and current of the motor are known, E_z is calculated according to equation 15. Here, if $E_z.I_a \cong V_{dc}.I_{dc}$ then it can be $E_z \cong V_{dc}$. If the DC-DC converter duty cycle D is known, V_{pv} can be predicted as in equation 16.

$$V_{dc} \cong V_{pv}(\frac{D}{1-D}) \quad (16)$$

III. SENSORLESS MPPT METHOD

In PV systems, temperature and radiation changes change the value of the power obtained from the panel. Increases in temperature and decreases in radiation value reduce the maximum power obtained from the panel. On the other hand, the voltage value at which maximum power will be achieved varies due to different radiation values falling on the panels. For this reason, various algorithms must be used to obtain maximum power under both uniform radiation and partial shadowing conditions.

The main purpose of the proposed MPPT method is to estimate the maximum power point by measuring only the motor current and speed without measuring the current and voltage of the PV system. Thus, a significant advantage will be achieved in system cost. Generally, current and speed values of the motor must be obtained to control. Speed data can be estimated using sensorless control techniques. However, it is assumed that speed is measured in this study. First of all, as seen in Equation 11, the mechanical power of motor is obtained from the product of the back emf and the motor current. Accordingly, obtaining maximum mechanical power from the motor will approximately mean drawing maximum power from the PV system. Since there is a motor, DC-DC converter and inverter in the system, the efficiency of the system is not fully known.
Because efficiency of the system will vary at different motor speeds and switching frequencies. For this purpose, a two-stage MPPT algorithm has been proposed, first approximately estimating the region of the MPP and then reaching the exact value.

In the first stage, the increasing back emf value with a small increase amount is given as the input reference. Since the speed and parameters of the motor are known, the motor back emf is calculated and the voltage of the motor and therefore the inverter input voltage is determined approximately. Depending on the increasing reference voltage value, a PI controller determines the duty cycle for switching the DC-DC converter and the motor is accelerated by increasing the voltage. The output voltage of the DC-DC converter is actually the same as the DC link voltage of the inverter and is calculated approximately. Using Equation 16, the input voltage of the DC-DC converter, that is, the voltage produced by the PV system, is obtained approximately. As the motor accelerates, its mechanical power will increase and the power value to be transferred by the PV system will change. The mechanical power of the motor will be calculated instantly and the maximum generated power will be recorded using sampling blocks and the GMPP point will be determined approximately. When the maximum input voltage to be applied to the motor is reached, the second stage MPPT algorithm is started. In the second stage, the initial duty cycle value was determined by using duty cycle obtained at the maximum power value in the first stage. Here, the maximum power point is found with the modified P&O algorithm using the motor's current and speed values, and the motor continues to operate at this point. The flow chart of the proposed algorithm can be seen in Figure 3.

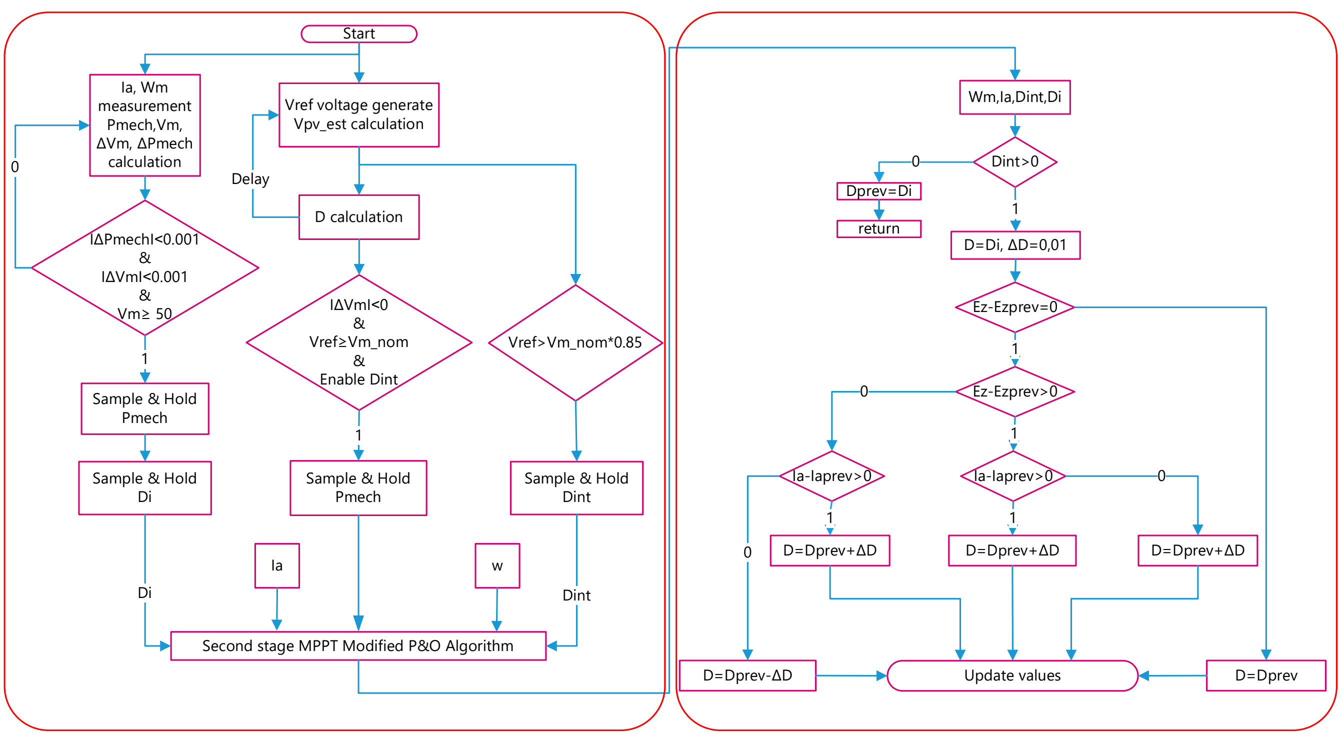

Fig.3. Flow chart of the proposed algorithm

IV. Simulation and Results

The simulation study has been performed by using MATLAB/Simulink. The MATLAB/Simulink blocks of simulation are shown in Figure 4. The water pump shows a non-linear load characteristic with high inertia. For this reason, the BLDC motor accelerates slower and different load torque occurs on the motor at different speed values. This behavior causes difficulties in the operation of MPPT algorithms. Since maximum power is obtained at different voltage levels, especially in partial shading conditions, it becomes difficult to accelerate the motor. In the simulation study, in order to create the torque characteristic of the non-linear pump load, the load torque of the motor was created to vary with the square of the speed. The proposed algorithm has been tested under four different PSCs, as depicted in Figure 5. In these PSCs, maximum power was generated at different voltage points, and the proposed algorithm was tested in various regions. Four different PSCs were created to test the proposed algorithm. The voltage level at which maximum power occurs in each of these atmospheric conditions is located in different regions. The created PSCs and their maximum power under these conditions are illustrated in Figure 5.

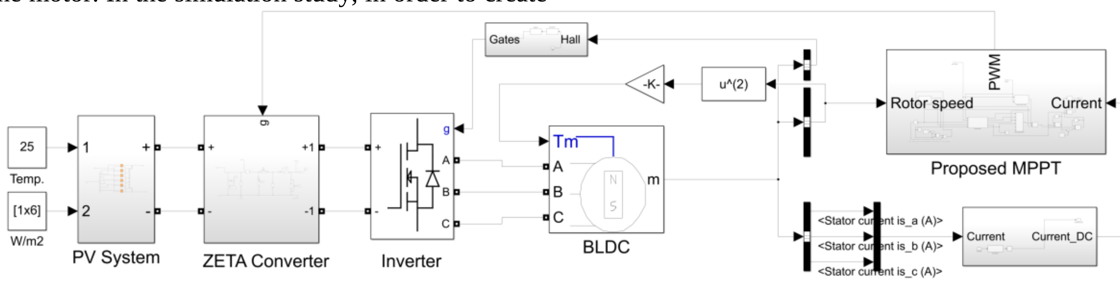

Fig.4. MATLAB/Simulink blocks of PV pump system

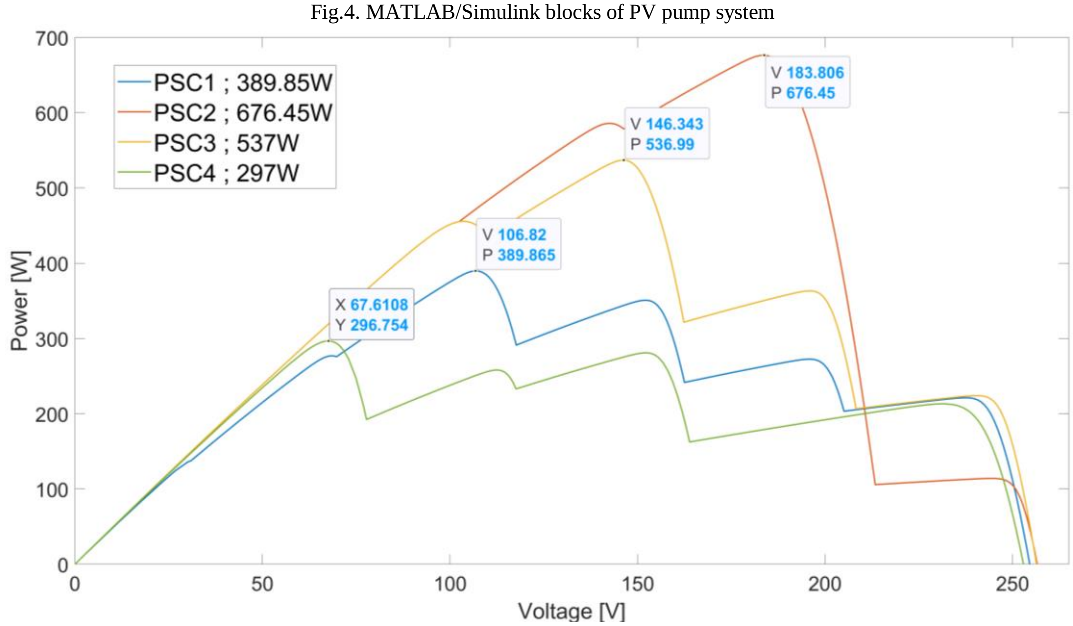

Fig.5. PV graph for four different PSC cases used in the simulation

Figure 6 shows the motor speeds and power of the PV system for four different PSC cases. Accordingly, the first stage MPPT algorithm was completed in 1.3 s, and the second stage MPPT started. When the power values obtained from the PV system were examined, a PV power of 389.683W was under PSC1 and the MPPT efficiency has been obtained as 99.95% in a steady state. When the PV system operated under PSC2, the power of the PV system measured as 647.114W, and the MPPT efficiency was found to be 95.66%. MPPT efficiencies under PSC3 and PSC4 conditions were obtained as 99.9% and 99.7%, respectively.

When the obtained results were examined, it was observed that the proposed algorithm worked only under PSC2 conditions with slightly lower efficiency than other conditions. Indeed, this efficiency value is at an acceptable level; however, very high efficiency has been achieved under other conditions. An important advantage of the proposed algorithm is its ability to the need for current and voltage information from the PV system, and PV system parameters are not required. The most important advantage of the scanning algorithm is its ability to approximately determine the power of the PV system using motor data. Figure 7 shows the current and voltages of the PV system. Accordingly, it can be seen that the completion of MPPT in Stage 2 does not depend on a specific period of time. However, at steady state is achieved in less than 2 seconds for all scenarios.

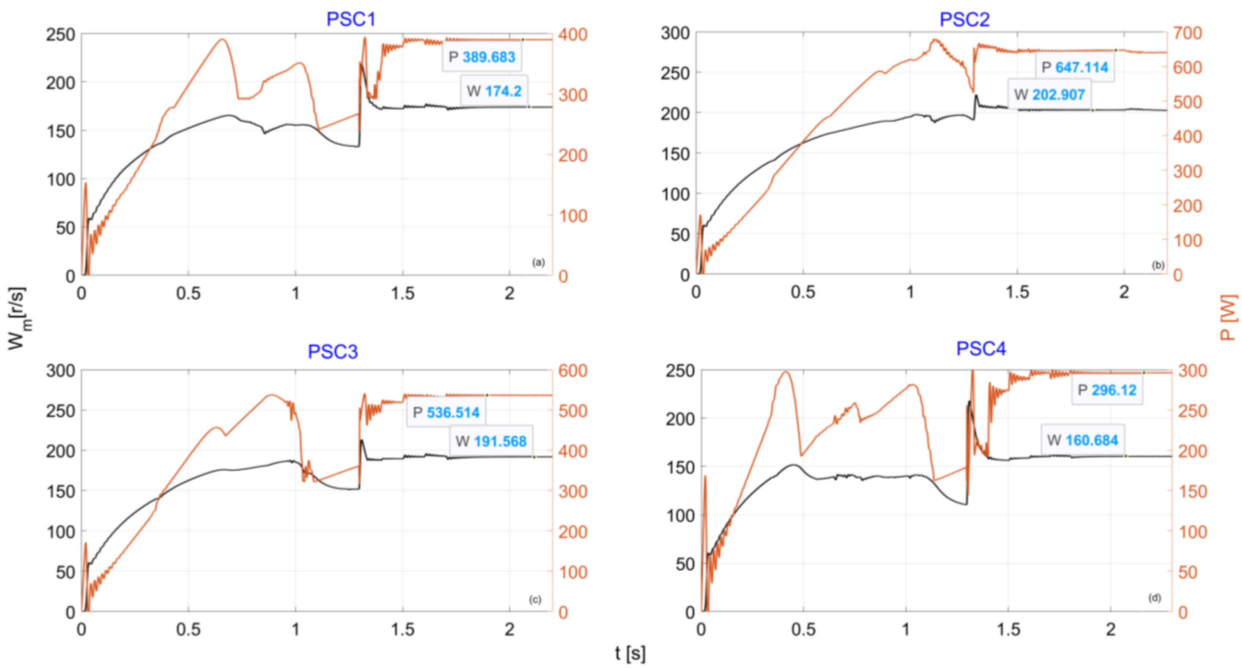

Fig.6. PV Powers and motor speeds obtained using the proposed algorithm a) PSC1 b)PSC2 c)PSC3 d)PSC4

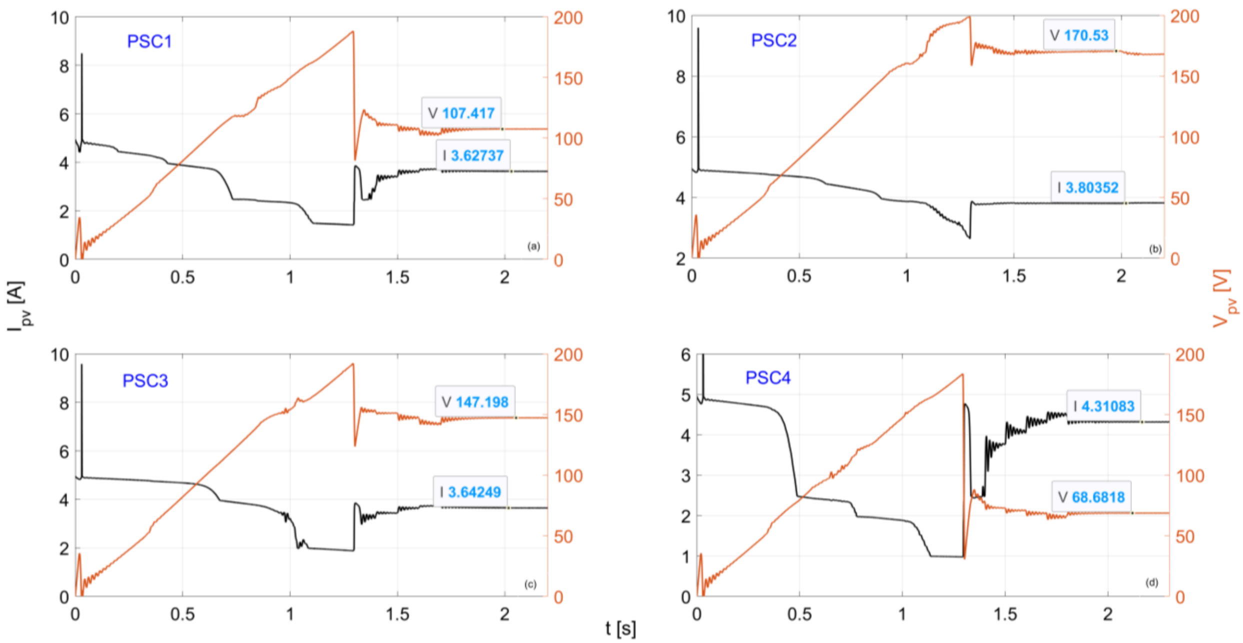

Fig.7. PV voltage currents obtained using the proposed algorithm a) PSC1 b)PSC2 c)PSC3 d)PSC4

Figure 8 illustrates the duty cycles occurring in four different PSC situations. This duty cycle is produced as a result of the operation of the MPPT algorithm. The duty cycle adjusts the voltage of the DC-DC converter. Although the running time of the MPPT algorithm appears to be long, it is not actually very long because the pump connected to the motor has a moment of inertia, slowing down the acceleration of the motor. If the motor could act as a resistive load, this scanning process could be completed much faster.

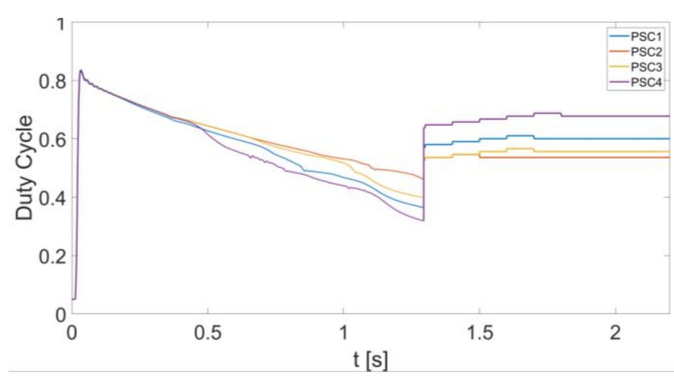

Fig.8. Duty cycles obtained using the proposed algorithm

In Figure 9, motor phase currents are shown for four different PSC conditions. When MPPT moves to the second stage, it is observed that the motor current remains approximately constant or undergoes small changes because the second stage operates in a very narrow area. This situation is evident when examining the change in duty cycles in Figure 8.In fact, this indicates that the efficiency of the MPPT continuous state is high and the tracking efficiency is also high. This is because when the first stage is completed, the maximum PV power has been greatly approached.

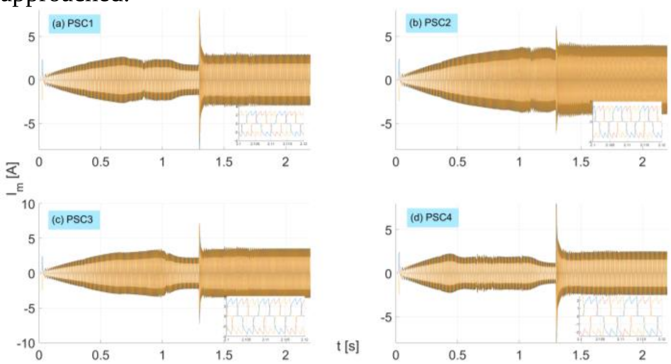

Fig.9. Motor phase currents obtained using the proposed algorithm

Since the proposed algorithm is a two-level hybrid MPPT algorithm, the first level detects the voltage region while the second level provides maximum power. The algorithm used at the second level in this study can be implemented with simple and low-level microcontrollers. More efficient and faster algorithms can be developed at the second level by using artificial intelligence-based, fuzzy-based and optimization-based algorithms. The most important problem here will be the use of complex algorithms that will increase the system cost. Because it will be necessary to use high-level microcontrollers and the system cost will increase. Additionally, it would be very difficult to develop these algorithms for nonlinear load. However, nonlinear loads can be driven more easily by using adaptive MPPT algorithms. In future studies, adaptive MPPT methods that adapt quickly to variable load conditions and have a simple structure can be developed to achieve higher efficiency. In this study, engine speed information was obtained assuming a sensor was used. Nowadays, a lot of research is being done on sensorless controls of BLDC motors. There are effective speed control applications by measuring only current and back-emf information. Therefore, in ongoing studies, a lower-cost system can be obtained by speed detection without using an engine speed sensor. In addition, malfunctions and maintenance costs arising from the speed sensor may be minimal.

V. Conclusion

In this study, a hybrid MPPT algorithm was developed for the PV pump system. In this system, BLDC is used as the motor. The output of the PV system is connected to a DC-DC ZETA converter. The converter output creates the input voltage of the inverter. The operation of the PV pump system was examined through simulation in the MATLAB/Simulink environment. The simulation study demonstrated that the proposed hybrid MPPT algorithm works with high efficiency under partial shading conditions. While the lowest MPPT efficiency was 95.66%, the highest efficiency was 99.9%. When the literature is examined, it is seen that the current and voltage information of the PV system is used for MPPT in photovoltaic pump systems using BLDC motors. In addition, system efficiency in PSC cases is also an important research topic. The fact that the proposed MPPT algorithm does not require information about the PV system is a significant advantage. The MPPT algorithm was carried out in two stages, using only motor current and speed information without measuring the current and voltage of the PV system. Thus, it is aimed to reduce the system cost. This study contributes significantly to the literature as a sensorless MPPT technique. However, this algorithm can be further improved. In future studies, especially the two-stage MPPT algorithm will be implemented in a single stage using artificial intelligence techniques. In addition, using artificial intelligence-based methods instead of the modified P&O algorithm used at the second level will significantly increase MPPT performance.

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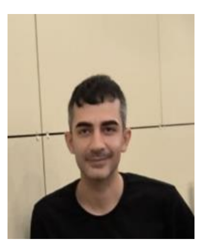
BIOGRAPHIES



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