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Research Article

Comparative Analysis of Voltage Segmentation ($0.8V_{oc}$) and Sensorless MPPT Algorithms in PV Pump Systems Operating Under Partial Shading Conditions

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ABSTRACT

When photovoltaic (PV) irrigation systems operate under partial shading conditions (PSC), traditional methods are insufficient. In addition to modified traditional methods, artificial intelligence and optimization-based smart methods are used to obtain maximum power from PV systems operating under PSC. These methods use one or more of the PV system's current, voltage, and atmospheric environment variables. In this study, a sensorless Maximum Power Point Tracking (MPPT) algorithm was developed. The proposed algorithm uses the values of the current and speed of the Brushless Direct Current Motor(BLDC) which used in the PV irrigation system. The current, voltage and other parameters of the PV system was not used. The proposed algorithm was compared the 0.8Voc method that used panel data. The proposed MPPT algorithm was tested with a simulation study created in the MATLAB/Simulink environment. In the simulation study, four different PSCs were created and the 0.8Voc method was compared with the proposed method. The obtained results are shown graphically. Accordingly, the superiority of the proposed method was observed in all cases except for the PSC2 case. On the other hand, there is a clear superiority in the speed of the 0.8Voc method. The proposed sensorless MPPT technique operated the PV pump system with high efficiency as 99.9% in the case of PSC1, 95% in the case of PSC2, 99.9% in the case of PSC3 and 99.7% in the case of PSC4.

1. INTRODUCTION

With the developing technology, the need for energy sources is increasing day by day. Due to the rapid depletion of traditional fossil fuel energy sources and their harmful effects on the environment, interest in renewable energy sources is increasing. Solar energy is one of the most important of these sources. Photovoltaic panels (PV) are used to obtain electrical energy from solar energy. However, the efficiency of these panels is quite low. For this reason, various maximum power point tracking (MPPT) algorithms have been developed to extract maximum power from the panels [1]. The Perturb&Observe (P&O) and Incremental Conductance (InC) algorithms emerged as the oldest MPPT algorithms. These algorithms are still preferred today due to their ease of application and simple structure [2]. These algorithms work by observing the changes in voltage and current obtained as a result of changing the duty cycle of the DC-DC converter. Thus, increasing or decreasing the duty cycle according to the status of the PV system power provides maximum power from the PV system. However, modified versions of these methods have also been used and are still being developed in order to respond faster to rapid atmospheric changes and to reduce fluctuations in the steady state [3,5].

The 0.8Voc technique is derived from the Constant Voltage technique, one of the oldest well-known algorithms. This method is performed by determining the PV system voltage at which maximum power occurs. Then, the system is operated at this voltage point with a controller. In recent years, high-performance methods that can operate under challenging atmospheric conditions have been developed. The simplicity of the method has emerged as the most important advantage [6,7]. There are more than one MPP in PV systems operating under partial shading conditions (PSC). However, only one of them is the Global Maximum Power Point (GMPP). The 0.8Voc technique has been reinterpreted by calculating the voltage inflection points and controlling these points. Thus, a high-efficiency method operating in the PSC has been developed [8]. A high-efficiency MPP algorithm derived from the 0.8Voc algorithm has been developed. The voltage region can be selected by using voltage reference. This algorithm detects GMPP by monitoring power changes [9]. Similarly, the performance of a simple, high-efficiency voltage scanning algorithm that observes power changes and finds the GMPP by performing a voltage scanning process has been investigated [10]. An algorithm that finds GMPP by obtaining I-V and P-V curves of PV arrays is actually a developed version of the 0.8Voc technique [11]. In another technique where the artificial intelligence algorithm is used, the current of the panels in the PV array is measured and entered into the artificial intelligence algorithm. The data obtained as output is the voltage value at which GMPP is formed. High efficiency has been obtained from this algorithm that works quite fast [12]. A two-stage algorithm has been proposed in a very recent study. In the first stage, the voltage regions are scanned and the MPP is detected, and in the second stage, the P&O algorithm is run at this point. Thus, the high performance of a new very efficient MPPT algorithm has been proven by simulation and experiment [13]. When the literature is examined, many studies based on the basic principles of the 0.8Voc algorithm are seen. The most important disadvantage of this method is the need to know the panel data with high accuracy. For this reason, different methods such as voltage scanning have also been developed.

Optimization based MPPT algorithms work with high performance in both normal solar irradiation and PSC. Although it has been the subject of much work in recent years, PSO (Particle Swarm Optimization) [14], CSA (Cuckoo Search Algorithm) [15], GWO (Gray Wolf Optimization) [16] and WOA (Whale Optimization Algorithm) [17] seem to be the most widely used optimization algorithms. However, the complex and demanding processing load of these algorithms is a significant disadvantage.

PV systems are used intensively in providing energy for irrigation systems. It is mandatory to use MPPT algorithms in these systems. Motors and pumps used in PV systems exhibit a non-linear load characteristic. Therefore, traditional methods respond late to rapid changes in atmospheric conditions and under PSC or are inadequate. A study has been conducted for a water pumping system with a PV-fed BLDC motor operating without a position sensor. The need for current sensors to measure motor phase currents in the system has been eliminated. The speed is automatically adjusted using an MPPT according to the highest power produced by the PV panel [18]. DC-DC converters are generally used to adjust the MPPT point in PV systems. DC-DC converters increase the system installation cost. Therefore, a PV pump system that feeds the BLDC pump without using a DC-DC converter has been developed [19]. Partial shading conditions are an important problem for PV irrigation systems. A study was presented that demonstrated the effect of PSC on the PV irrigation system through simulation and was verified experimentally [20]. In another study, BLDC was used to utilize the maximum power provided by the PV array and to increase the efficiency of the water pumping system. The proposed system used the CSA algorithm to obtain the MPP under partial shading conditions [21]. Synchronous reluctance motors are used in the industry with low cost and high efficiency. The MPP algorithm was developed without using a current sensor in a solar pump system using a synchronous reluctance motor. The PV system current was estimated using the system identification method and motor control data. This method, which operates with very high efficiency, showed very high performance under PSC [22]. In another study, the PSO method was used to operate the water pumping system using the PV-fed BLDC motor at maximum power point. In the study, it was proven that the PSO technique performed better than the traditional P&O technique [23]. A smart method using radiation and temperature values as input was used for the MPP algorithm. BLDC connected to a PV system was operated at maximum power point using this method [24]. Optimization of the MPPT algorithm has been performed for a grid-connected PV-fed pump system. To demonstrate the effectiveness of the proposed method, the algorithm has been tested for three different DC-DC converters [25].

In this study, a two-stage MPPT algorithm is proposed for a PV system using BLDC operating under PSC. In the first stage, the PV system voltage is estimated using motor information and the MPP is found by looking at the motor power while the voltage changes. In the second stage, a P&O using motor information is used to find the real MPP around the estimated value. A sensorless MPPT algorithm is developed without using panel data, PV system and current information. Thus, unlike traditional algorithms, the system installation cost has been reduced. In addition, the problems that may arise from sensor errors have been reduced. Because the number of sensors used in the system has been reduced. In the proposed algorithm, motor current, speed and k coefficient, which is the parameter of the motor, are used. Simulation studies are performed using the MATLAB/Simulink program. The proposed algorithm is tested under four different PSCs.

2. PV IRRIGATION SYSTEMS

In this study, the PV irrigation system consists of PV panels, Zeta type DC-DC converter, three-phase inverter, BLDC and pump load. Here, the ZETA DC-DC converter is used for the operation of the MPPT algorithm.

2.1. PV System Model

A single diode model was used as the PV cell model. The equations of this model are seen between Equation 1 and Equation 3.

$$I = I_{PV} - I_D - I_{R_P} \quad (1)$$

$$I = I_{PV} - I_0\left[exp\left(\frac{V + R_s I}{a}\right) - 1\right] - \frac{V + R_s I}{R_p} \quad (2)$$

$$a = \frac{N_s nkT}{q} \quad (3)$$

Here I_0 represents the reverse saturation current and leakage current. a is the ideality factor, N_s is the number of series-connected cells, n is the ideal diode constant, k is the Boltzmann constant (1.3806503x10-23 J/K), T is the cell temperature (Kelvin), q is the electron charge (1.60217646x10-19 C). The current produced by the PV panel under the influence of light is shown in Equation 4.

$$I_{PV} = \left(I_{pv,n} + K_1(T - T_n)\right)\frac{G}{G_n} \quad (4)$$

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

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

Here $I_{SC,n}$ is the nominal short circuit current, $V_{OC,n}$ is the open circuit voltage, K_I is the current coefficient and K_V is the voltage coefficient. In this study, the PV system consists of 6 series-connected panels. The model of the panel used in the simulation study is TPB125x125-72-P. The voltage produced by a panel at the maximum power point is given as 35.3V and its power as 154.967W. Accordingly, the maximum power that the PV system can produce is calculated as 929.8W at 211.8V.

2.2. BLDC and Pump Model

BLDC has a 3-phase stator winding. There are permanent magnets in its rotor. The position of the rotor is detected by field effect sensors placed inside the stator. The mathematical model of BLDC is shown in Equation 6.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ M & L-M & M \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{6}$$

Here V_A,V_B,V_C are phase voltages, i_a, i_b, i_c are phase currents, R is winding resistance, L is winding self-inductance and M is mutual inductance. The motor is switched with a six-step switching technique using the logic information coming from the field effect sensors. The simplicity of the switching technique is the most important advantage of this motor. The pump load connected to the motor is modeled to increase depending on the square of the speed. The expression of the load torque is seen in Equation 7. The parameters of BLDC used in the simulation study are given in [18].

$$T_L = k * \omega^2 \tag{7}$$

2.3. Zeta DC-DC Converter

Zeta converter is structurally composed of two coils, two capacitances and one diode. The basic circuit diagram of ZETA converter is shown in Figure 1. Here, the zeta converter, which includes components such as L_1 input inductor, L_2 output inductor and C_1 intermediate capacitor, is designed to always operate in continuous conduction mode.

The zeta converter is a fourth-order DC-DC converter that can operate in either boost or buck mode. This feature provides an unlimited area for maximum power point tracking. Unlike a conventional step-down converter, the zeta converter has a continuous output current. The output inductor makes the current continuous and ripple-free.

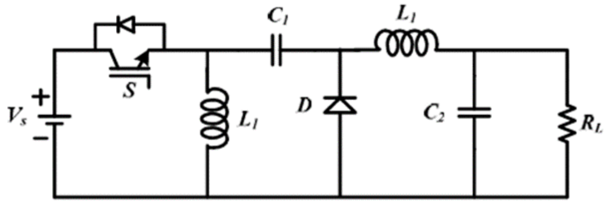

Figure 1. Zeta DC-DC Converter

The mathematical model used in the ZETA converter design is given between Equation 8 and Equation 12.

$$D = \frac{V_{dc}}{V_{dc} + V_{mpp}} \tag{8}$$

$$I_{dc} = \frac{P_{mpp}}{V_{dc}} \tag{9}$$

$$L_1 = \frac{D.V_{mpp}}{f_{sw}.\Delta I_{L1}} \tag{10}$$

$$L_2 = \frac{(1-D).V_{mpp}}{f_{sw}.\Delta V_{C1}} \tag{11}$$

$$C_1 = \frac{D.I_{dc}}{f_{sw}.\Delta V_{C1}} \tag{12}$$

Here D is the duty cycle and its estimate is given in Equation 8. V_{dc} is the average output voltage of the zeta converter. The average current flowing through the inverter is given in Equation 9. After D and I_{dc} are calculated approximately, L_1, L_2 and C_1 can be calculated as seen in Equations from 10 to 12.

3. 0.8V_{OC} and PROPOSED MPPT ALGORITHM

In PV systems, there may be uniform (homogeneous) radiation on the panels, as well as PSC where the radiation values on the panels are different. In this case, maximum power can be drawn by finding the highest MPP among the different MPPs. An example of the power changes obtained as a result of working under uniform radiation and PSC is given in Figure 2.

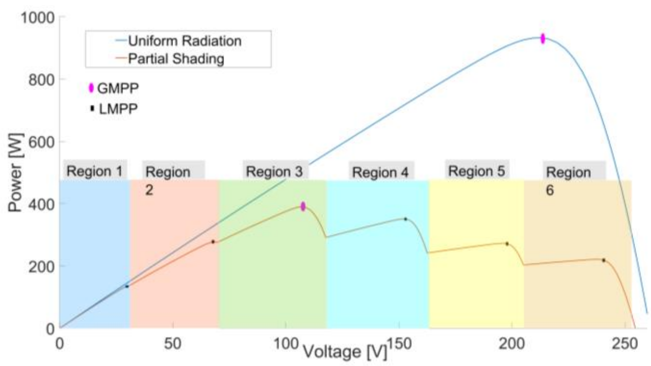

Figure 2. P-V graph resulting from uniform radiation and PSC in the PV system.

3.1. 0.8V_{oc} MPPT Method

While many traditional methods can be effective in the case of uniform sunlight, different MPPT algorithms need to be developed in PV systems operating under PSC. The 0.8Voc value is used to obtain the MPP using the open circuit voltage of the PV array when the panels operate under uniform radiation. When the PSC is examined, it is noted in Figure 2 that MPP has formed in 6 different regions in the system where 6 panels are connected in series. In this technique, the coefficient of 0.8 is not definite in every application. However, it is seen that a value close to this is used in applications. Knowing the maximum power in each system is related to both the accuracy of the panel data and whether the coefficient used finds the definite value of the MPP. In PV systems operating under PSC, as the number of serial panels increases, the voltage of each panel is added and MPP is found in each region. For example, while the panel open circuit voltage in Region 1 is 43.5V, the voltage value at which the maximum power occurs is determined as 35.3V. In the 2nd region, while the open circuit voltage is 87V, the voltage value at which the maximum power is generated is found to be 69.6.

These voltage values are calculated for all regions and operation is provided at these voltages for each region respectively. The maximum power value obtained in each region is calculated. Finally, the voltage of the region where the largest maximum power is generated constitutes the reference voltage. The system continues to operate at this voltage with the help of a controller.

3.2. Proposed MPPT Algorithm

First, the reference voltage (V_{ref}) signal is generated between 1 and 220V to increase linearly for 1.5s. The DC line input at the inverter input is approximately determined using the speed and current information of the motor. The PI controller output generates the duty cycle for switching the ZETA converter. Since the inverter DC line voltage and duty cycle are sampled and known at the same time, the converter input voltage and therefore the PV system output voltage are estimated from the ZETA DC-DC converter output voltage equation. As the reference voltage increases, the amount of change in the motor voltage and the amount of change in the mechanical power of the motor (ΔV_m *and* ΔP_{mech}) are calculated.

When $|\Delta V_m| < 0.001$ & $|\Delta P_{mech}| < 0.001$ & $V_m > 50$ condition is met, mechanical power and duty periods are sampled. When the $V_{ref} > V_{m\_nom} * 0.85$ condition is met, Dint>0 becomes and the second stage is passed. In the second stage, the motor's back emf and current are checked to ensure that the motor's speed reaches its maximum.

The proposed algorithm consists of two stages. In the first stage, the PV system voltage at the MPP is estimated and this is an approximate value. Because the motor, inverter and DC-DC converter efficiencies are not taken into account. In the second stage, an improved form of the P&O algorithm that uses motor current and speed values is used to find the exact MPP point in the estimated voltage region. The flow chart of the proposed algorithm is given in Figure 3.

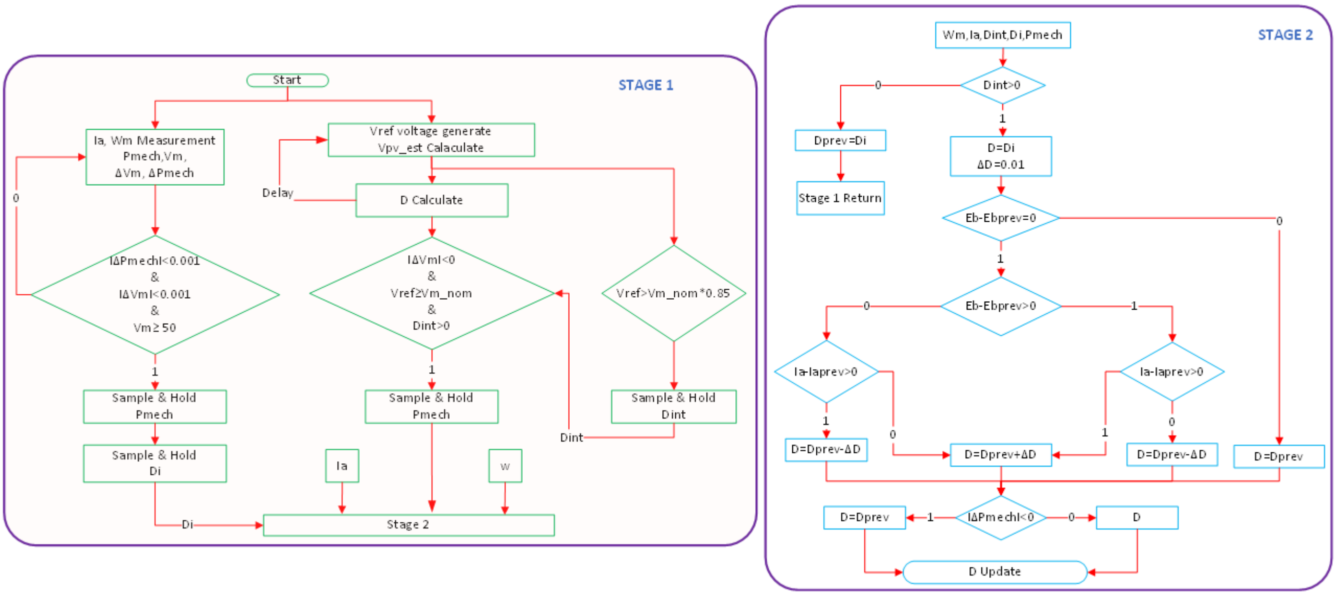

Figure 3. Flow chart of the proposed MPPT algorithm.

4. SIMILATION OF THE PROPOSED ALGORITHM

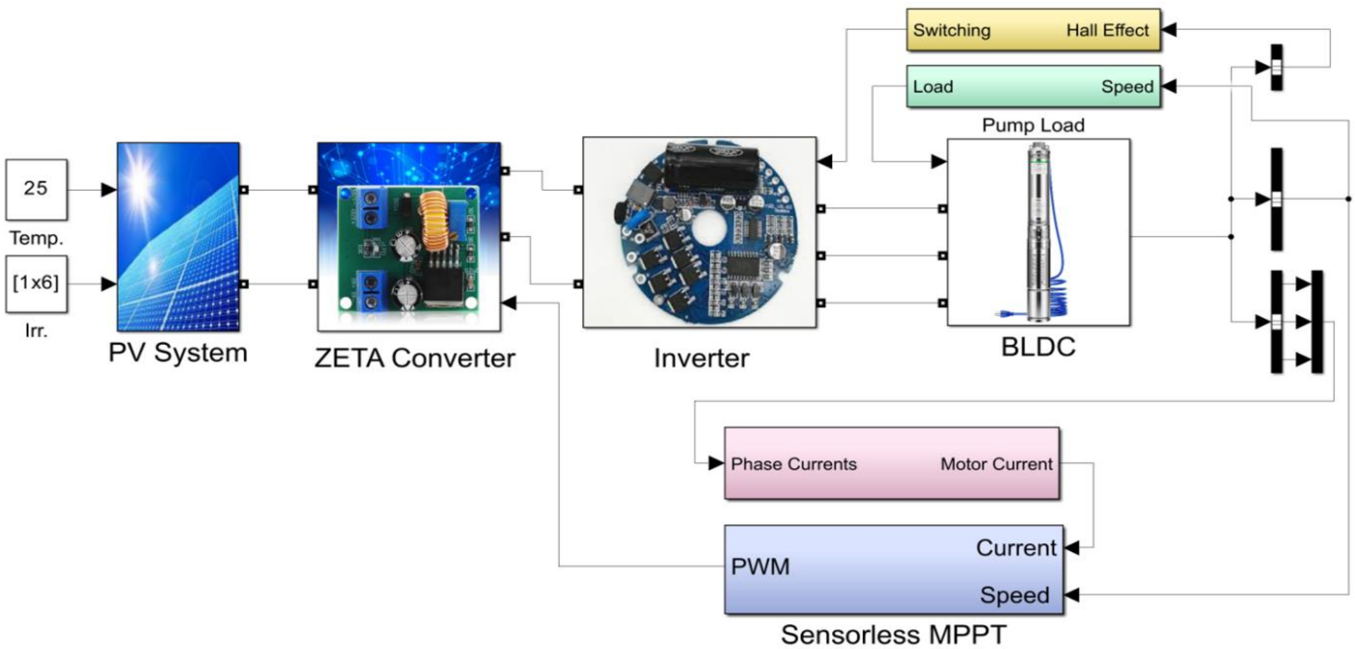

Figure 4. MATLAB/Simulink simulation of the PV pump system

In this study, 6 series-connected panels, each of which can produce 155W power at 35.3V, were used. While the total output power of the PV system is 930W, this power is produced at approximately 212V voltage. Here, the nominal power of the motor selected for the load is 746W and its nominal speed is 2000 rpm. ZETA DC-DC converter was used to run the MPPT algorithm. Figure 4 shows the PV pump system created in the MATLAB/Simulink environment.

The proposed algorithm and 0.8Voc technique were tested for four different atmospheric conditions where the PSCs were formed. The P-V graphs of the PSCs used for testing are shown in Figure 5.

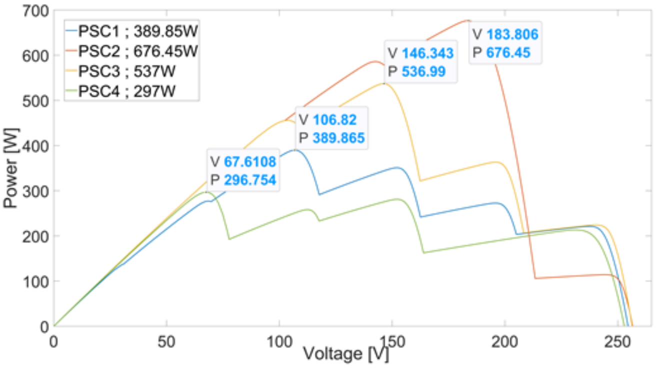

Figure 5. Maximum powers obtained from PV systems operating under four different PSCs

Figure 6 shows the power graphs obtained using 0.8Voc and the proposed MPPT techniques for four different PSCs. When Figure 6 is examined in detail, a much faster MPPT capture time is seen for all atmospheric conditions in the 0.8Voc method.

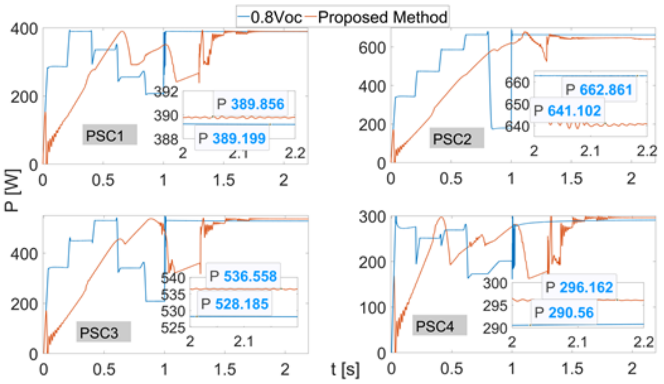

Figure 6. Power obtained using 0.8Voc and proposed MPPT methods in four different PSC

In the case of PSC1, there is a very small power difference between the proposed algorithm and the 0.8Voc method, but the proposed method was able to produce more power. The efficiency of the proposed method is greater than 99.9% and almost completely captures the maximum power. In the case of PSC2, the proposed algorithm was able to produce less power than the 0.8Voc method. The efficiency of the proposed method is approximately 95%. Although this efficiency value seems low, it is sufficient for many applications. The power value obtained from the PV pump system operating under PSC3 conditions is seen as 536.514W. In this case, the power value that can be obtained from the PV system is known as 537W. The efficiency of the MPPT algorithm in the steady state is calculated as 99.9%. The obtained value is higher than the 0.8Voc value. When the PSC4 case is examined, the power value obtained from the PV system is 296.16W. The maximum power value that can be obtained from the PV system is known as 297W. The steady state efficiency of the MPPT algorithm was determined as 99.7%.

Figure 7 shows the PV system voltage and current values obtained using 0.8Voc and the proposed method for four different atmospheric conditions.

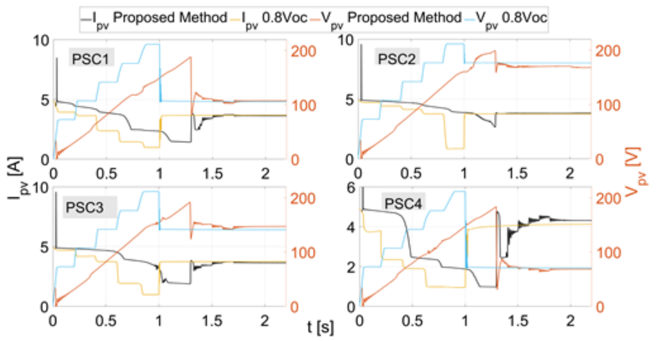

Figure 7. Power values obtained with 0.8Voc and proposed MPPT methods

Figure 8 shows the motor speeds obtained for both methods under all atmospheric conditions.

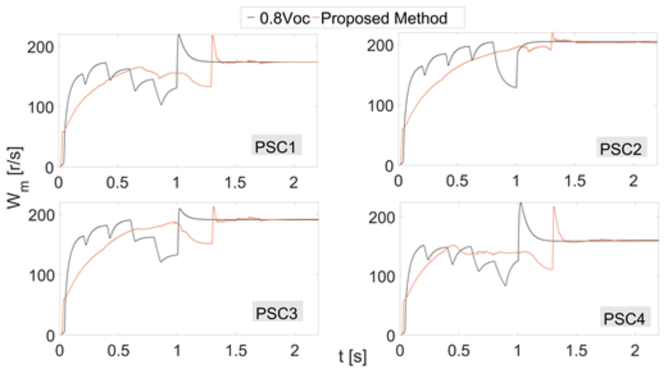

Figure 8. Speed of the BLDC motor obtained with 0.8Voc and proposed MPPT methods

Figure 9 shows the duty periods obtained using 0.8Voc and proposed method in all atmospheric conditions.

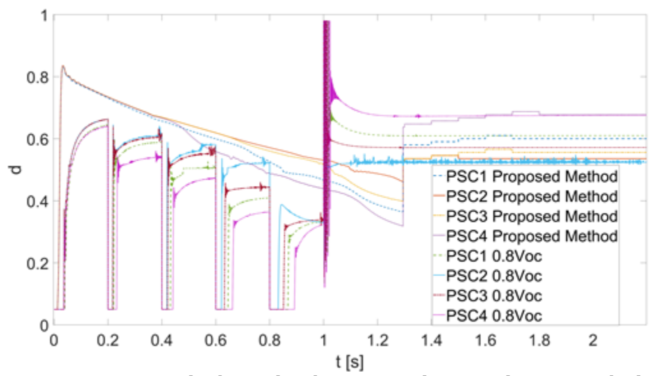

Figure 9. Duty periods obtained with 0.8Voc and proposed MPPT methods

When the proposed method is used, there is a very small decrease in motor speed in PSC2. Because the power transferred to the motor is approximately 20W less than the 0.8Voc method. The low maximum power value in PSC2 may be due to the synchronization disorder between the measurement value and the processing time. In order to both increase the speed of the proposed method and to prevent the negative situation that occurs in PSC2, the P&O algorithm in the second stage can be modified to approach the maximum power with smaller changes. In addition, a direct duty cycle scanning algorithm can be developed instead of the voltage scanning algorithm seen in the first stage. In future studies, research will be continued for all scenarios.

In the 0.8Voc technique, if the coefficient of 0.8, which is the coefficient to be multiplied by the open circuit voltage, can be precisely determined to obtain the maximum power, faster results can be obtained. However, this requires excessive dependence on panel data. The data of the panels must be known perfectly. However, there is no dependence on panel data in the two-stage proposed algorithm. In addition, it does not require the measurement of current-voltage data of the PV system and environmental variables. The success of the proposed algorithm has been superior except for the PSC2 case. The most important advantage of the proposed algorithm is that it is both a sensorless method and superior to the traditional 0.8Voc method in many different cases. On the other hand, the operating speed of the algorithm is slower than the 0.8Voc method.

The proposed algorithm can be easily implemented with cheap microcontrollers due to its simple structure. Since it does not use the current and voltage values of the PV system, sensor costs are reduced. Thus, the initial installation cost of the system is reduced. In addition, since it does not need panel data, it can be easily integrated into different PV systems.

5. CONCLUSION

In this study, a simulation study of a PV pump system using BLDC motor and ZETA DC-DC converters was carried out. When operating under PSC in PV pump systems, conventional MPPT techniques are insufficient. At the same time, conventional methods measure one or more of the environment variables along with the current and voltage information of the PV system in addition to the motor current and speed information. Some methods such as 0.8Voc can only achieve superior success when they know the panel data perfectly. On the other hand, panel data may change over time depending on the operation and environment variables.

In this study, a two-stage MPPT technique is proposed. In this technique, k coefficient, current and speed information of the motor are used. No data such as current and voltage of the PV system is used in the proposed algorithm. In the first stage, the region where maximum power occurs is estimated approximately. In the second stage, the MPP point is found exactly. The proposed algorithm is tested under four different PSCs in MATLAB/Simulink environment. The proposed algorithm is compared with the 0.8Voc method under these different conditions. Except for the atmospheric condition of PSC2, the proposed algorithm is superior. However, it is seen that the speed of the proposed 0.8Voc method is higher than the proposed algorithm. The proposed sensorless MPPT technique operated the PV pump system with high efficiency as 99.9% in the case of PSC1, 95% in the case of PSC2, 99.9% in the case of PSC3 and 99.7% in the case of PSC4.

In future studies, the scanning speed of the algorithm will be increased by choosing smart methods in the first or second stage. In addition, different situations such as PSC2 will be examined and the algorithm will be made to work with higher efficiency. On the other hand, studies will continue to operate the system with high efficiency by measuring the speed of the motor without a sensor.

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