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# A review on development of photovoltaic water pumping system

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ABSTRACT

Photovoltaic (PV) water pumping system has been becoming increasingly important in remote, isolated, and non-electrified population, where either accessibility to the grid is difficult to establish or implementation cost is indeed very high. In such location, PV water pumping application is significant area of interest for sustainable development. In this article, DC and induction motor as part of multi and single stage water pumping system has been reviewed. The maximum power point (MPP) at which PV system is to be operated is tracked by peak power tracker to utilize solar power. Therefore, the peak power tracking algorithms with voltage, current, duty cycle, and frequency as perturbation parameters under uniform and non-uniform insolation are also presented. Review reports on PV emulators used for evaluation of new MPPT control techniques, and microcontroller based implementations of MPPT controller are also presented. Thus, this article becomes reference document for developing DC/AC PV water pumping system.



**Contents**



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## 1. Introduction

The solar energy is fast gaining importance due to climate change mitigation policies, programmes, and rapid depletion of conventional sources of energy. Government of India, in its Jawaharlal Nehru Solar Mission toward building SOLAR INDIA proposes off-grid solar applications up to 200 MW (2010–2013) in Phase I, 1000 MW (2013–2017) in Phase II, and up to 2000 MW (2017–2022) in Phase III [1]. Environment friendly solar energy is abundant in nature, and most parts of India receive 4–7 kWh of solar radiation per square meter per day with 250–300 sunny days. The solar energy is utilized either in its thermal form or in photovoltaic form. Applications which use the thermal form of solar energy are cookers, water heaters, dryers, water purifiers, etcetera. The lanterns, street lighting, home lighting, and water pumping are few applications which use the photovoltaic form of energy.

Photovoltaic (PV) systems are modular and have a low running cost as no moving parts are involved. PV modules have a comparatively long life and the balance of system (BOS) requires minor maintenance. However, PV systems suffer from a high initial investment cost, low solar-to-electric power conversion efficiency, and non-linear voltage-current (*V-I*) characteristics. Notwithstanding these drawbacks, PV systems have emerged as one of the most potent alternative energy source to grid power supply for feeding stand alone applications.

The major interest in the subject is in reducing the pay-back period in terms of improved efficiency and performance, as well as, reducing the number of components to decrease overall cost. Therefore, researchers have been focusing on three major areas,

- Manufacturing process of solar arrays: many research efforts have been taking place to improve the manufacturing process of PV cells and its material [2–4].
- Controlling the insolation input to the PV arrays: The intensity of insolation impinging on the surface of the PV array is maximized by using sun-tracking solar collectors [5], [6] or by rearrangement of solar cells configuration of PV array corresponds to changes in environmental conditions [7], [8].
- Utilization of output electric power of the solar arrays: efforts are being made to improve effective utilization of solar energy in off-grid / on-grid PV stand alone applications [9–21].

The reasons for reviewing PV water pumping systems in particular are that the grid power supply fed pumps used for potable and irrigation purposes experience four important problems; a. Cost of motor burn outs and its repair due to voltage fluctuations, b. Lower crop yields due to irrigation activities affected by shortages in the supply of electricity, c. Transmission & distribution losses and d. This has been made affordable by utilizing the government subsidies which affects growth in developing countries. Moreover, advancements in design of motors, availability of cost effective high speed digital signal controllers, decrease in the cost of photovoltaic modules, rapid developments in the state-of-art power conversion devices, as well as, topologies of power circuit, and more significantly, the policies of the government have accelerated the growth of PV applications.

PV water pumping system [22–24] is broadly classified as DC and AC motor pumping systems [25]. The DC motor based PV water pumping systems consist of a PV array, with or without an intermediate converter, and a motor coupled with a pump. The AC motor water pumping systems requires a DC-AC inverter for converting intermediate converter output voltage or directly PV voltage in to a variable voltage / variable frequency power source. The intermediate converter employed with a peak power tracking algorithm matches the load impedance to the optimum internal impedance of the PV array in order to utilize the optimum solar power. The point at which this occurs is called the maximum power point (MPP). The MPP varies for changing insolation and temperature in addition to wind, dirt, etcetera. The dynamic adjustment of the MPP at which the PV system is to be operated to extract the maximum power is called maximum power point tracking (MPPT). This controller is called MPPT controller, and it is implemented invariably with a DC-DC converter and a peak power tracking algorithm. In a parallel development, the induction motor based water pumping system which is referred here as AC water pumping system has found much interest among researchers due

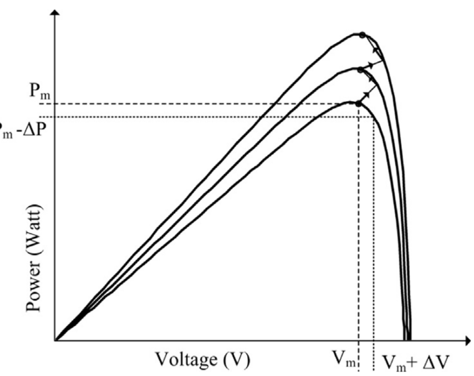


**Fig. 1.** Effect of perturbation on V-P characteristics and MPP variations.

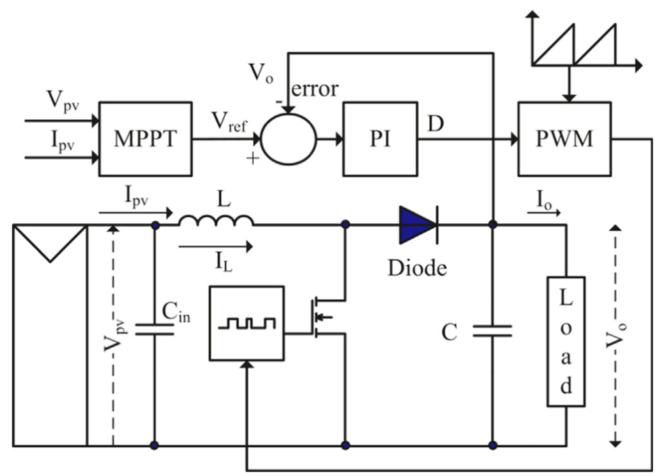


**Fig. 2.** MPPT Tracking using a DC-DC converter in Voltage Mode Control.

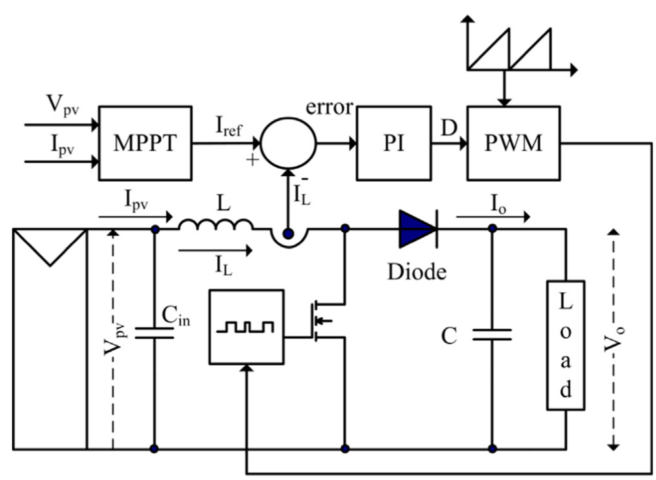


**Fig. 3.** MPPT Tracking using a DC-DC converter in Current Mode Control.

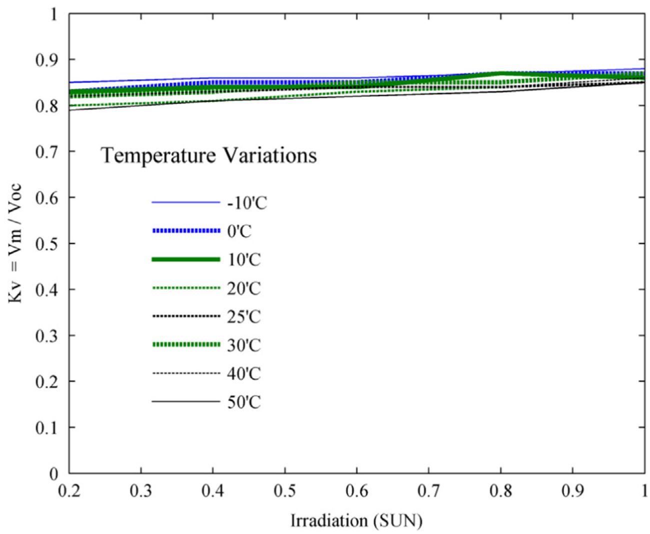


**Fig. 4.** Variation of Factor $k_v$ for changes in insolation at different temperature.

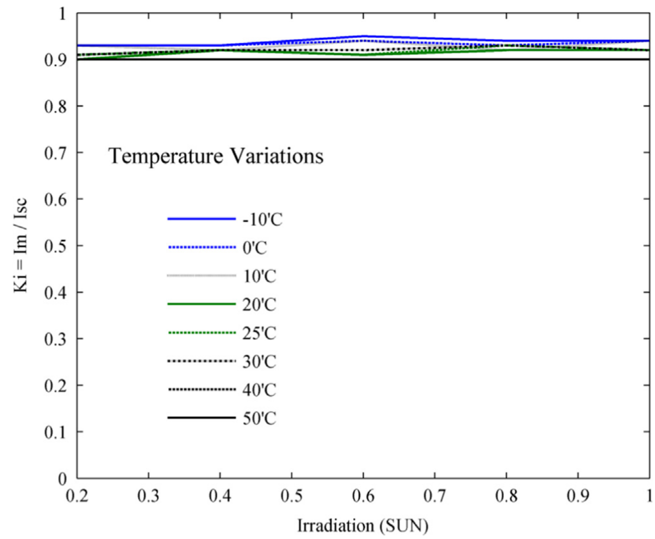


**Fig. 5.** Variation of factor $k_i$ for changes in insolation at different temperature.

to its low cost, low maintenance, high reliability, rugged design, small sizes, and availability of high efficiency motors.

Off-grid stand-alone water pumping systems utilizing induction motors can be classified as multistage and single stage. In both systems, the water storage tank is considered as an indirect energy storage device instead of battery modules to completely utilize the solar power. The size of the tank should be compatible with the capacity of the PV array and the maximum possible insolation at the location of usage.

The comprehensive review report on DC motor pump with peak power tracking algorithms, induction motor as a part of multi and single stage water pump are presented. Single stage water pumping system is high efficient, low cost, and simple to control. Therefore, more emphasis is given for single stage system. The MPP tracking under partially shaded condition is difficult to achieve due to multiple peak displayed by voltage-power (*V-P*) characteristics of PV array. Hence, peak power tracking algorithms under partially shaded insolation are overviewed. The microcontroller based system is fast gaining importance in PV system, and thus it is also reported. It is always important to evaluate the newly developed MPPT algorithms without using PV array. The references which present procedure for validating MPPT algorithms without using actual PV modules are presented.

## 2. DC motor water pump

In early 1980 s, the starting, steady state, and transient performances of solar power fed DC motors for linear and centrifugal pump load torques were analyzed for photovoltaic applications without intermediate converters [26–30]. These motors were bulky, and require frequent maintenance. Solar power fed permanent magnet brushless DC (PMBLDC) motors have been used for water pumping applications with and without intermediate converter [31–34]. The intermediate converters are in general DC-DC converters. These are used to track the peak power point and operate the PV system at the same point to completely utilize solar power. Peak power tracking algorithms are reviewed in detail as follows,

### 2.1. Peak power tracking algorithms

The controller which tracks the MPP consists of a power electronic converter working with any one of the peak power tracking algorithms. The objective of the MPPT controller is to find the voltage $V_m$ or current $I_m$ at which the PV system should be operated to utilize the maximum PV power $P_m$ during changes in atmospheric conditions. In a DC-DC converter based MPPT controller, the reference voltage or current is perturbed either with a positive step if the slope of power is positive or with a negative step if the slope of the power is negative to approach the MPP as depicted in Fig. 1 using either voltage mode control as shown in Fig. 2 or current mode control as shown in Fig. 3 [35–37].

The MPP can also be tracked by perturbing directly on the duty ratio. The different MPPT techniques which use the power electronic converters, mainly a DC-DC converter to vary the current coming from a PV array have been reported in the literature [38–40]. Many MPPT techniques have been developed and have been continuously improved by researchers in terms of simplicity, sensor reduction, speed of response, cost, range of effectiveness, hardware implementation, etcetera [40–48]. Among the various MPPT algorithms reported, look-up tables, fractional open circuit voltage, fractional short circuit current, and usage of a test cell are simple and easy to implement [49]. The reported popular perturbation methods are Hill-climbing (HC) [50], Perturb and Observe (PAO) [51], [52], Incremental Conductance (IncCond) [53], [54], and Artificial Intelligence (AI) methods [55–57]. The fundamental MPPT techniques are discussed in the following paragraph.

#### 2.1.1. Look-up table method

In this technique, all the requisite data for changes in insolation and temperature is recorded and stored in the memory. This technique is simple and it exhibits a fast response in tracking the MPP. However, it is difficult to record and store all possible data of atmospheric variations. Moreover, it requires a large memory capacity [14], [15].

#### 2.1.2. Fractional open-circuit voltage

The optimum linear relationship between $V_m$ and $V_{oc}$ of the PV array for varying insolation and temperature levels results in the fractional open-circuit voltage MPPT method. The relation is given by,

$$V_m = k_v V_{oc} \tag{1}$$

where $k_v$ is a constant of proportionality and it is dependent on the characteristics of the PV array used in the application. The constant $k_v$ is determined beforehand by measuring $V_{oc}$ and $V_m$ at different insolation and temperature levels [49].

The simulation results given in Fig. 4 shows that the factor $k_v$ lies in between 0.79 and 0.88 for variation of insolation from 20% to 100% for temperature variations from -10 °C to 50 °C. $V_{oc}$ is measured by opening a switch connected in series to the PV array.

### 2.1.3. *Fractional short-circuit current*

Under varying insolation and temperature, $I_m$ is related approximately linear to the $I_{sc}$ of the PV array and it is given by [9],

$$I_m = k_i I_{sc} \tag{2}$$

where $k_i$ is proportionality constant and it is dependent on the characteristics of the PV array in use. From Fig. 5, $k_i$ is found to lie between 0.9 and 0.94 for the variation of insolation at the temperature span of -10 °C to 50 °C. When a boost DC-DC converter is used, $I_{sc}$ is measured by shorting a converter switch periodically. In any other arrangements, an additional switch is needed to short the PV array for the measurement of $I_{sc}$ which increases the number of components and cost.

### 2.1.4. *Test cell method*

In fractional open-circuit and short-circuit current techniques, shorting and opening of the PV array is done at the rate of switching frequency. During this period, the power delivered to the load is affected. Therefore, the measurement of $V_{oc}$ or $I_{sc}$ is done with a dummy cell which is expected to match the characteristics of an active cell. However, it is difficult to have same characteristics of a dummy cell as that of an active cell and it also increases the cost [58].

### 2.1.5. *Constant voltage control*

In this method, the true MPP voltage is approximately equal to the regulated reference voltage, since variation of $V_m$ for changes in insolation is small. This method can be implemented by the measurement of $V_{pv}$ alone using a DC-DC converter. This method is represented by [59],

$$V_{ref}(n) = \begin{cases} V_{ref}(n-1) + \delta V V(n) < V_{ref} \\ V_{ref}(n-1) V(n) = V_{ref} \\ V_{ref}(n-1) - \delta V V(n) > V_{ref} \end{cases} \tag{3}$$

This technique performs sufficiently well for low insolation. For higher insolation, this method is combined with other methods to get satisfactory results.

### 2.1.6. *Perturbation techniques*

In perturbation techniques, the value of an operating parameter, such as voltage, current, and duty cycle is incremented or decremented to approach the MPP through predefined step size based on the changes in power observed in previous perturbation. These techniques do not depend on the PV module specifications. They are independent of variations in temperature, insolation, wind, dirt, and aging. However, these techniques take finite time to identify the MPP, and the PV system oscillates around the MPP. The oscillation can be minimized by using smaller step sizes. However, a smaller step size slows down the MPPT process. As a solution to this situation, the variable perturbation step size which becomes smaller as it approaches the MPP has been considered [50], [53], [54]. Perturb and Observe (PAO), Hill Climbing (HC), and incremental conductance (IncCond) are the perturbation MPPT techniques. They are invariably used in PV systems.

*2.1.6.1. Hill climbing / perturb and observe.* HC perturbs the duty ratio of a DC-DC converter which causes changes in the PV current and voltage [50]. It is given by eq. (4),

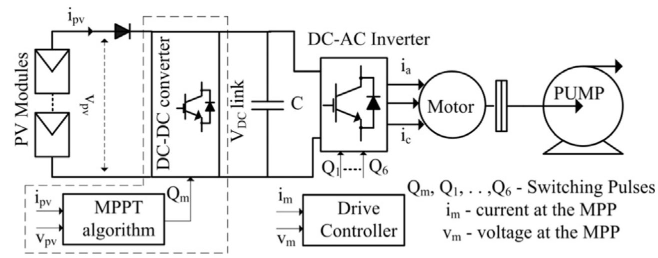


**Fig. 6.** Block Diagram of multistage PV water pumping system.

$$Dutyratio_{ref}(n) = \begin{cases} Dutyratio_{ref}(n-1) + \delta V P(n) > P(n-1) \\ Dutyratio_{ref}(n-1) P(n) = P(n-1) \\ Dutyratio_{ref}(n-1) - \delta V P(n) < P(n-1) \end{cases} \tag{4}$$

In the PAO MPPT technique, the operating voltage of the PV array is perturbed as given in eq. (5) when voltage mode control of a DC-DC converter is employed.

$$V_{ref}(n) = \begin{cases} V_{ref}(n-1) + \delta V P(n) > P(n-1) \\ V_{ref}(n-1) P(n) = P(n-1) \\ V_{ref}(n-1) - \delta V P(n) < P(n-1) \end{cases} \tag{5}$$

Thus, when the MPP is tracked, HC and PAO methods utilize different ways to realize the same fundamental concept. Both methods can fail for sudden variation of insolation [11], [12].

*2.1.6.2. Incremental conductance.* The incremental conductance method is based on the fact that the derivative of the PV output power with respect to the PV voltage in $V$ - $P$ characteristics of the PV array is zero at the MPP, positive to the left of the MPP, and negative to the right as given by eq. (6),

$$\begin{cases} \frac{dP}{dV} = 0 \text{atMPP} \\ \frac{dP}{dV} > 0 \text{ left of MPP} \\ \frac{dP}{dV} < 0 \text{ right of MPP} \end{cases} \tag{6}$$

When instantaneous power is differentiated with respect to voltage,

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \tag{7}$$

The relation between incremental and instantaneous conductance at the MPP is given by,

$$\begin{cases} \frac{\Delta I}{\Delta V} = -\frac{I}{V} \text{ at MPP} \\ \frac{\Delta I}{\Delta V} > -\frac{I}{V} \text{ left of MPP} \\ \frac{\Delta I}{\Delta V} < -\frac{I}{V} \text{ right of MPP} \end{cases} \tag{8}$$

The direction of the required change in the control variable so as to move the PV voltage toward the MPP is determined by comparing the instantaneous conductance to the incremental conductance and is given by,

$$V_{ref}(n) = \begin{cases} V_{ref}(n-1) + \delta V \frac{\Delta I}{\Delta V} > -\frac{I}{V} \\ V_{ref}(n-1) \frac{\Delta I}{\Delta V} = -\frac{I}{V} \\ V_{ref}(n-1) - \delta V \frac{\Delta I}{\Delta V} < -\frac{I}{V} \end{cases} \tag{9}$$

This algorithm exhibits comparatively good results for sudden variations of atmospheric conditions [53], [54]. It also introduces smaller oscillations around the MPP than the PAO method. However, its implementation is not simple as compared to the PAO method.

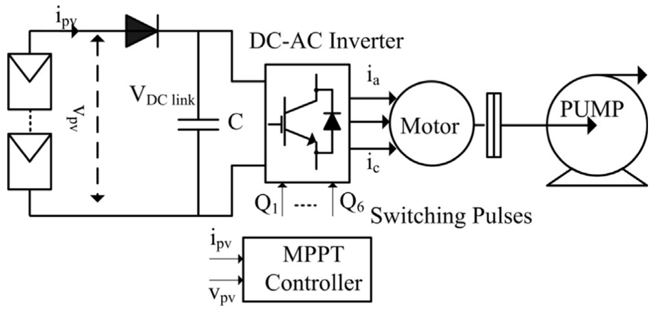


**Fig. 7.** Block Diagram of a single stage PV water pumping system.

**Table 1**
Multi criterion algorithm technique.

| Measurement | | | Sign | State of the PV array |
|---|---|---|---|---|
| dP | dV | dI | | |
| < 0 | < 0 | < 0 | − | Insolation decrease |
| < 0 | < 0 | ≥ 0 | − | Current source |
| < 0 | ≥ 0 | < 0 | + | Voltage source |
| > 0 | < 0 | ≥ 0 | + | Voltage source |
| > 0 | ≥ 0 | < 0 | − | current source |
| > 0 | > 0 | < 0 | + | Insolation increase |
| = 0 | | | 0 | MPP |
| $F_e(n) = F_e(n-1) + \text{sign} \times f_e$ | | | | |

## 3. Induction motor water pump

Literature review has been conducted on multi and single stage PV water pumping systems. They are presented as below,

### 3.1. Multi stage PV water pumping system

The multistage water pumping system comprises of a PV array, a DC-DC converter, a DC-AC inverter, and an induction motor coupled to a pump as given in Fig. 6 [60–66]. The induction motor based water pumping systems have been investigated, and continuously improved in terms of tracking of solar power, as well as, performance and efficiency of the drive.

Contrary to the DC motor water pumping systems, an AC motor can't be directly connected to the PV source. In the first stage, a DC-DC converter is used to track the peak power point using any one of the algorithms discussed above, and then a DC-AC inverter is used to convert DC voltage in to variable voltage / variable frequency power source. When field oriented control (FOC) technique is considered for controlling an induction motor drive [60], the optimum torque and flux producing components are determined using eq. (10) to eq. (14) operate the system at optimum power point.

$$i_{mr} = fn(\omega_m) \tag{10}$$

$$T^*_{em} = P_m/\omega_m \tag{11}$$

$$i^*_{qs} = T^*_{em}/(k_t i^*_{mr}) \tag{12}$$

$$i^*_{ds} = i^*_{mr} + \tau_r p(i^*_{mr}) \tag{13}$$

$$\omega_{sl} = i^*_{qs}/(\tau_r i^*_{mr}) \tag{14}$$

The vector rotator is calculated by adding the slip frequency to either the measured or the estimated mechanical speed of the motor. The current controlled PWM is employed to switch the voltage source inverter to generate a variable voltage / variable frequency power source. This is called multi stage water pumping system. It has been continuously developed and is based on how the optimum power point determined by using a DC-DC converter is used to determine the three control loops, namely, speed, torque, and flux control loops parameters [61–65]. The indirect FOC and direct torque control (DTC) with a virtual speed sensor can also be implemented to improve the performance [67]. The induction motor drive system performance has been improved by varying the frequency with respect to the determined optimum power. A variable frequency based drive also has been discussed for a water pumping system, in which variable frequency based operation has proved to be a highly efficient technique [68]. In this system, once the optimum power is determined, the frequency at which the drive is operated can be calculated for parabolic and linear loads respectively as,

$$f_s = \sqrt[3]{p_m/p_{mn}}(f_{sn}) \tag{15}$$

$$f_s = \sqrt[2]{p_m/p_{mn}}(f_{sn}/\xi) \tag{16}$$

These equations are computationally complex to determine using low cost microcontrollers. Moreover, the frequency is slowly ramped up / down according to the calculated values unlike the case of FOC or DTC which exhibit better transient responses. This leads to the emergence of single stage PV water pumping systems. In this system, frequency is slowly ramped up / down until the power consumed by water pump matches the optimum power of the PV array using MPPT algorithms considering frequency as the perturbation parameter.

### 3.2. Single stage PV water pumping system

A single stage water pumping system is shown in Fig. 7. This is a simple, low cost and an efficient architecture for a PV water pump with minimized losses, and reduced maintenance. In this system, a DC-DC converter is not required, since a DC-AC inverter with a tracking algorithm performs the same task, in addition to generating a variable voltage / variable frequency power supply in order to feed the induction motor [69–72].

This system requires a voltage and a current sensor for both the operations of controlling the drive and MPPT, since any change in the load impedance is reflected as a change in voltage and current of the PV array. When the motor is not operated, the DC link voltage is equal to the open circuit voltage ($V_{oc}$) of the PV array. In case of an overloaded or short circuit condition, the maximum current is equal to the short circuit current ($I_{sc}$) of the PV array. For a given PV current, increased slip decreases the load impedance which in turn increases rotor current and decreases magnetizing current.

Therefore, the tracking of solar power is directly related to the utilization of power or improvement in the active component of the induction motor. A single stage PV water pumping system with a six step mode of switching has been reported in the literature. In this system, the simple PAO MPPT technique based on frequency perturbation is presented. This PAO technique is confused during starting of the motor and tracking due to machine dynamics [69]. The multi criterion algorithm (MCA) method which is derived from an incremental conductance method is suited for rapid variations of insolation. The perturbation step size is varied based on changes in voltage. However, the changes in voltage are not large for the changes in insolation [70]. The standard frequency drives can also be used with single stage water pumping system [71]. In such systems, the six element circuit which consists of two diode, two capacitor, and two resistors is proposed. The transient across the PV array varies the frequency setting of the variable frequency drive [72].

The MPPT techniques based on frequency perturbation are appropriate for single stage PV water pump drive systems. In a single stage PV water pump drive system, the speed is ramped up or down by perturbing the frequency in a positive or a negative direction based on changes in voltage, current, and power to approach the MPP. The constant voltage control, PAO, and incremental conductance or multi criterion algorithm are the important MPPT techniques for single stage PV water pump systems. These techniques are reproduced in the following sections with respect to frequency perturbation [69], [70].

#### 3.2.1. Constant voltage control

In solar stand alone water pump system, the command frequency is increased when the PV voltage is higher than the reference voltage. Otherwise, the command frequency is decreased as given in eq. (17). This is the most stable technique among all MPPTs. However, this method can't be applied separately in the PV system [70].

$$F_e(n) = \begin{cases} F_e(n-1) + \delta f V(n) > V_{ref} \\ F_e(n-1) V(n) = V_{ref} \\ F_e(n-1) - \delta f V(n) < V_{ref} \end{cases} \tag{17}$$

#### 3.2.2. Perturb and observe

The PAO method is popular due to its ease of implementation. It tracks well when the insolation doesn't change rapidly [69]. Under fast variations of insolation, this method may regulate the speed in the wrong direction. When this technique is implemented, logic has to be incorporated to differentiate the peak during starting of the motor from the actual MPP, since this method behaves as if MPP has been identified during the starting of the motor. This technique is represented as,

$$F_e(n) = \begin{cases} F_e(n-1) + \delta f dP > 0 \\ F_e(n-1) dP = 0 \\ F_e(n-1) - \delta f dP < 0 \end{cases} \tag{18}$$

#### 3.2.3. Incremental conductance

The incremental conductance technique explained by considering the reference voltage as a perturbation parameter can be modified with respect to frequency perturbation, and it is given by [70],

$$F_e(n) = \begin{cases} F_e(n-1) + \delta f \frac{I}{V} + \frac{\Delta I}{\Delta V} < 0 \\ F_e(n-1) \frac{I}{V} + \frac{\Delta I}{\Delta V} = 0 \\ F_e(n-1) - \delta f \frac{I}{V} + \frac{\Delta I}{\Delta V} > 0 \end{cases} \tag{19}$$

#### 3.2.4. Multi criterion algorithm

In general, an MPPT controller utilizing IncCond algorithm can operate the PV system at the MPP with an improved transient and steady state performance. When a fixed point microcontroller is used to implement this technique, analog-to-digital converter data of voltage and current are represented by same data format. This causes computational difficulties. Hence, the direction of the perturbation is misdirected when the criterion $I/V + \Delta I/\Delta V$is calculated because of the absolute value smaller than 1, it is considered as zero.

Moreover, when the solar insolation varies quickly resulting the status of change in voltage and current as$\Delta I > 0$, and$\Delta V > 0$. According to this condition, the frequency is decreased causing degradation in performance of the drive system. Therefore, from eq. (19), it is possible to remove the divide and multiply operations by simply verifying the sign of change in voltage, current, and power as shown in Table 1. This is called multi criterion algorithm [70].

## 4. MPPT algorithms for partially shaded conditions

The algorithms which determine MPP under partially shaded condition are discussed for power supply and grid interface applications [73–79]. In these systems, a DC-DC converter is controlled comparatively at lesser sampling period to sweep the PV voltage range. When it is found that a current peak is lower than the peak occurs during sweeping, the corresponding peak is latched as current operating point. The MCA, PAO, and IncCond algorithms are effective only for uniform insolation. Patel and Agarwal [80] have studied the *I–V* and *P-V* characteristics of large scale PV systems under partially shaded conditions (PSC) using a MATLAB / SIMULINK® model. Two-stage tracking techniques have been proposed to identify the Global MPP (GMPP) amongst the multiple MPPs under partially shaded conditions (PSC) [73], [74]. In the first stage, open-circuit voltage ($V_{oc}$) and short-circuit current ($I_{sc}$) are measured or a simple linear function [81] is used to move closer to the vicinity of Global MPP followed by the use of any one perturbation MPPT method in the second stage to reach the actual MPP.

## 5. Microcontroller based implementation

Microcontroller based implementations are reviewed for residential or power supply applications to understand the issues involved when a microcontroller based system is developed for a PV water pumping system. A microcontroller based control system is described for a residential PV power conditioning system [82–87]. The control functions are implemented using Intel 8751 an 8- bit microcontroller. The PAO MPPT controller based on voltage perturbation is presented for the power supply applications. It uses the buck type DC-DC converter in addition to the battery charger [88]. For AC powered appliances such as fluorescent lamps, fans, etcetera, PIC 16F873 is used to implement the control functions [89]. With the digital signal processor based implementation, the MPPT can be reached rapidly and accurately by increasing the sampling frequency in DC-DC converter system [83]. A two loop control technique implementation is discussed, but is reported to be a complex method [90]. The algorithm for partial shaded condition of insolation is considered and is implemented using a microcontroller [80].

## 6. PV Emulators for testing MPPT algorithms

The MPPT algorithms are tested under controlled conditions for their realization and for determination of their efficiency. The reported references discussed for grid system, power supply applications, and stand alone applications are reviewed to understand the testing and implementation procedure for a single stage PV water pumping system. The Agilent Technologies' Solar Array Simulator is usually used to test the algorithms under controlled conditions [39], [91]. But, they are expensive equipments and are only available up to a few hundred watts of power. Easwarakhanthan et al. [92] proposed a solar array simulator based on Commodore CBM-4016 microcomputer with an Adret DC voltage generator, a Keithley multimeter, and a power amplifier for testing up to a capacity of 750 W. The capacity expansion depends on the availability of suitable power amplifiers. A simple and low cost module based on the maximum power transfer theorem can be used to test the algorithms for power supply application [93]. An operational amplifier and transistor combination can also be used as a low cost solar emulator to evaluate MPPT algorithms [94]. A tungsten halogen lamp with a controlled power supply is used to test the algorithms based on switching frequency modulation [95].

## 7. Future scope

In photovoltaic water pumping system, the common objective is to decrease cost / watt [96–98]. The single stage water pumping system employing induction motor is worth to further investigate. In this system, the MPPT is achieved utilizing frequency dependent load impedance characteristics of induction motor. This results in selection of minimum MPPT sampling time equal to motor-pump time constant. The control system for improving the efficiency, performance of drives and peak power tracking process can be further examined under the condition of non uniform insolation, reduced components and to decrease the rotor slip losses of induction motor.

## 8. Conclusions

It is understood that the advancement in PV water pumping system leads to rural economy development. An extensive literature review has shown the background of PV based DC and AC motor based water pumping systems. The presented literature review thus can be used for development of real-time microcontroller based DC/AC PV water pumping drive systems and its validation for change in insolation and temperature. The tracking of MPP under uniform and non-uniform insolation is also presented.

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