



SOLAR PV POWERED WATER PUMPING SYSTEM USING DC MOTOR DRIVE: A CRITICAL REVIEW

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Abstract- This paper presents the review of the Solar Photovoltaic (SPV) array fed water pumping system using a DC Motor Drive. The penetration of renewable energy powered water pumping systems in industrial and domestic applications receiving wide attention nowadays. The introduction of a DC motor brings an improved solution to the commercial water pumping system. SPV array fed water pumping system using DC mainly consist the maximum power from the solar Photovoltaic (PV) array by restraining the duty ratio of the DC-DC boost converter. The results will be presented in terms of performance parameters such as total energy produced and total volume of water pumped and further validate that MPPT can significantly improve efficiency and performance of PV water pumping system compared to the system with and without MPPT.

Keywords: - Water Pumping System, Renewable Energy Sources, Photovoltaic System, Boost Converter and DC motor.

1. INTRODUCTION

Contemporarily more than 900 million people in various countries do not have potable water available for consumption. In isolated and rural areas the water supply only comes from the rain or distant rivers. In such places, the conventional pumping system is indecorous due to the unavailability of electric power. The use of SPV system is one of the perfect remedies for this problem [1]. This sort of energy source is cheaper and can be used to work for several years without the need for maintenance. Such systems are not new and are already used for more than three decades [2]. GDP of agriculture in India is around 16% and it plays an important role in Indian economy. Approximately 69 percentage of the population in India living in rustic areas and the sole source of their income is from agriculture and cognate activities. The water is the prerequisite for agriculture and the main water resource used for the agricultural purpose are rivers, canals, wells, and monsoons. Around 64% of cultivated land in India mostly depends on monsoons [2]. Irrigation is important to lessen the dependence on monsoons in India. In rural areas, diesel pump sets are used for irrigation but its maintenance cost is high and creates pollution. Motor pump set is used for water supply in those places where grid electricity exists. Grid connection is not available in all part of India, especially in remote areas. In such cases, stand-alone water pumping system is employed [1]. Negligible maintenance cost and pollution free operation are the main advantages of solar pumping system but installation cost is high for such systems. The lifespan of solar PV water pumping system is observed nearly around 25-30 years [1]. Different variety of motor-pump set configurations is used in the solar pumping system. The most conventionally employed pump type is the centrifugal pump. Solar PV shallow water pumping using single-stage centrifugal pumps are suitable for low head applications, while the multistage centrifugal pump is more suitable for PV subterranean water pumping and surface water pumping with high heads applications. Other pump types such as progressive cavity pumps and piston pumps have also been utilized. Both DC and AC motors are used for solar PV pumping applications.

2. SOLAR WATER PUMPING SYSTEM

Block schematic of solar PV water pumping system is shown in fig. 2.1. Solar panel drives the DC motor using DC-DC converter. The capital cost of the solar power plant is high hence its main aim is to acquire peak power from the installed plant. MPPT algorithms are used to gather maximum energy from the plants. A comparison study of different MPPT methods is described in [6]-[8]. Perturb and Observe is the most recurrently used MPPT algorithm particularly for low priced implementation. DC-DC converters such as a buck, boost, and buck-boost are used for solar pumping applications. The converters like buck and boost have the fewer number of components but the MPPT region is limited to such kind of converters. The buck-boost converters have boundless MPPT region and it also gives ripple free input-output current [4] [5]. The water pumping systems proposed in this paper are stand-alone type without backup batteries. The block diagram of various proposed photovoltaic motor pump systems are shown in Fig. 2.1. The system including the subsystems will be simulated to verify the functionalities. In this thesis various photovoltaic pump systems are proposed.

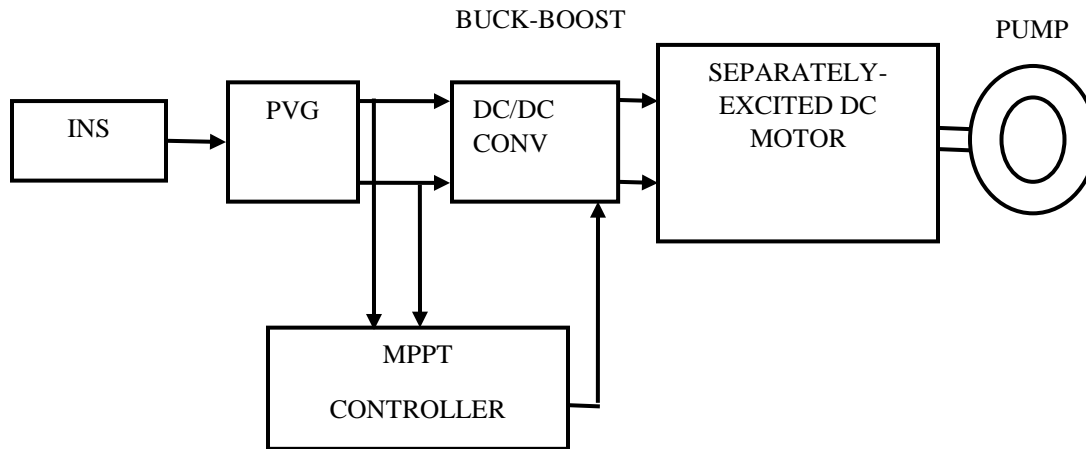


Fig. 2.1 PV fed Separately Excited DC Motor Pump System with MPPT

The proposed work is to simulate these photovoltaic pump systems and compare output mechanical power for different photovoltaic pump systems at different insolation level. For MPPT we use hill climbing algorithm.

3. PV MODULE SYSEM

The solar cell can be represented by the electrical model shown in Fig. 3.1. Its current voltage characteristic is expressed by the following equations

$$I = I_L - I_0 \left(e^{\frac{q(V-IR_S)}{AKT}} - 1 \right) - \frac{V-IR_S}{R_{sh}}$$

Where I and V are the solar cell output current and voltage respectively, I_0 is the dark saturation current, q is the charge of an electron, A is the diode quality (ideality) factor, k is the Boltzmann constant, T is the absolute temperature and R_S and R_{SH} are the series and shunt resistances of the solar cell. R_S is the resistance offered by the contacts and the bulk semiconductor material of the solar cell. The origin of the shunt resistance R_{SH} is more difficult to explain. It is related to the non-ideal nature of the p-n junction and the presence of impurities near the edges of the cell that provide a short-circuit path around the junction [14]. In an ideal case R_S would be zero and R_{SH} infinite. However, this ideal scenario is not possible and manufacturers try to minimize the effect of both resistances to improve their products. Sometimes, to simplify the model, as in [11], the effect of the shunt resistance is not considered, i.e. R_{SH} is infinite, so the last term in equation is neglected. A PV panel is composed of many solar cells, which are connected in series and parallel so the output current and voltage of the PV panel are high enough to the requirements of the grid or equipment. Taking into account the simplification mentioned above, the output current-voltage characteristic of a PV panel is expressed by below equation where n_p and n_s are the number of solar cells in parallel and series respectively [11].

$$I \approx n_p I_L - n_p I_0 \left(e^{\frac{q(V-IR_S)}{AkTn_s}} - 1 \right)$$

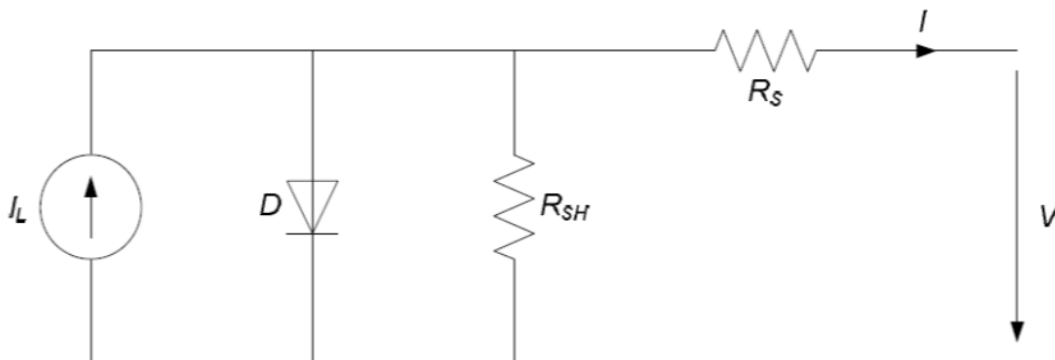


Fig. 3.1 Equivalent Circuit of a Solar Cell

4. OPEN CIRCUIT VOLTAGE, SHORT CIRCUIT CURRENT AND MAXIMUM POWER POINT

Two important points of the current-voltage characteristic must be pointed out: the open circuit voltage V_{OC} and the short circuit current I_{SC} . At both points the power generated is zero. V_{OC} can be approximated from 1st above

equation when the output current of the cell is zero, i.e. $I = 0$ and the shunt resistance R_{SH} is neglected. It is represented by below equations. The short circuit current I_{SC} is the current at $V = 0$ and is approximately equal to the light generated current I_L as shown in equation.

$$V_{OC} \approx \frac{AkT}{q} \ln \left(\frac{I_L}{I_0} + 1 \right)$$

$$I_s \approx I_L$$

The maximum power is generated by the solar cell at a point of the current-voltage characteristic where the product VI is maximum; this point is known as the MPP and is unique, as can be seen in Fig. 3, where the previous points are represented.

5. FILL FACTOR

Using the MPP current and voltage, I_{MPP} and V_{MPP} , the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}), the fill factor (FF) can be defined as:

$$FF = \frac{I_{mpp} V_{mpp}}{I_{sc} V_{oc}}$$

It is a widely used measure of the solar cell overall quality [14]. It is the ratio of the actual maximum power ($I_{MPP} V_{MPP}$) to the theoretical one ($I_{SC} V_{OC}$), which is actually not obtainable. The reason for that is that the MPP voltage and current are always below the open circuit voltage and the short circuit current respectively, because of the series and shunt resistances and the diode depicted in Fig. 3.1. The typical fill factor for commercial solar cells is usually over 0.70.

6. TEMPERATURE AND IRRADIANCE EFFECTS

Two important factors that have to be taken into account are the irradiation and the temperature. They strongly affect the characteristics of solar modules. As a result, the MPP varies during the day and that is the main reason why the MPP must constantly be tracked and ensure that the maximum available power is obtained from the panel.

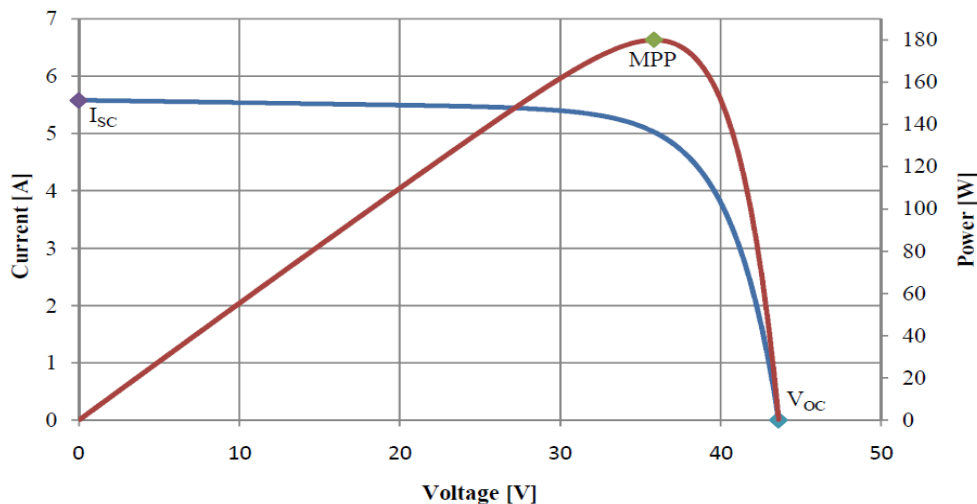


Fig. 6.1 Important Points in the Characteristic Curves of a Solar Panel

The effect of the irradiance on the voltage-current (V-I) and voltage-power (V-P) characteristics is depicted in Fig. 6.2, where the curves are shown in per unit, i.e. the voltage and current are normalized using the V_{OC} and the I_{SC} respectively, in order to illustrate better the effects of the irradiance on the V-I and V-P curves. As was previously mentioned, the photo-generated current is directly proportional to the irradiance level, so an increment in the irradiance leads to a higher photo-generated current. Moreover, the short circuit current is directly proportional to the photo generated current; therefore it is directly proportional to the irradiance. When the operating point is not the short circuit, in which no power is generated, the photo generated current is also the main factor in the PV current, as is expressed by 1st and 2nd above equations. For this reason the voltage-current characteristic varies with the irradiation. In contrast, the effect in the open circuit voltage is relatively small, as the dependence of the light generated current is logarithmic, as is shown in 4th above equation.

Fig. 6.2 shows that the change in the current is greater than in the voltage. In practice, the voltage dependency on the irradiation is often neglected [10]. As the effect on both the current and voltage is positive, i.e. both increase when the irradiation rises, the effect on the power is also positive: the more irradiation, the more power is generated. The temperature, on the other hand, affects mostly the voltage.



The open circuit voltage is linearly dependent on the temperature, as shown in the following equation:

$$V_{oc}(T) = V_{OC}^{STC} + \frac{K_V\%}{100}(T - 273.15)$$

According to just above equation, the effect of the temperature on V_{OC} is negative, because K_V is negative, i.e. when the temperature raises, the voltage decreases. The current increases with the temperature but very little and it does not compensate the decrease in the voltage caused by a given temperature rise. That is why the power also decreases. PV panel manufacturers provide in their data sheets the temperature coefficients, which are the parameters that specify how the open circuit voltage, the short circuit current and the maximum power vary when the temperature changes. As the effect of the temperature on the current is really small, it is usually neglected [10]. Fig. 6.3 shows how the voltage-current and the voltage-power characteristics change with temperature. The curves are again in per unit, as in the previous case.

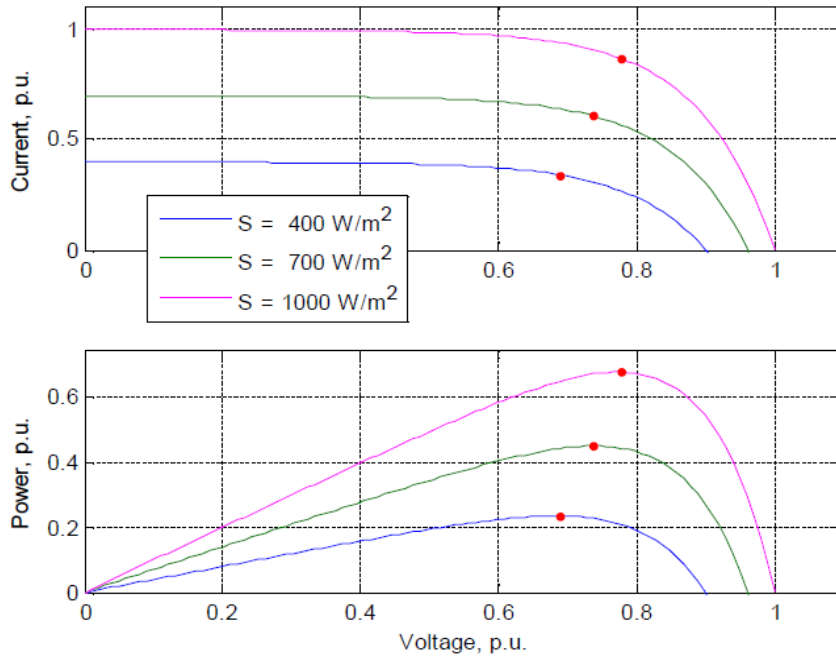


Fig. 6.2 V-I and V-P Curves at Constant Temperature (25°C) and Three Different Insolation Values

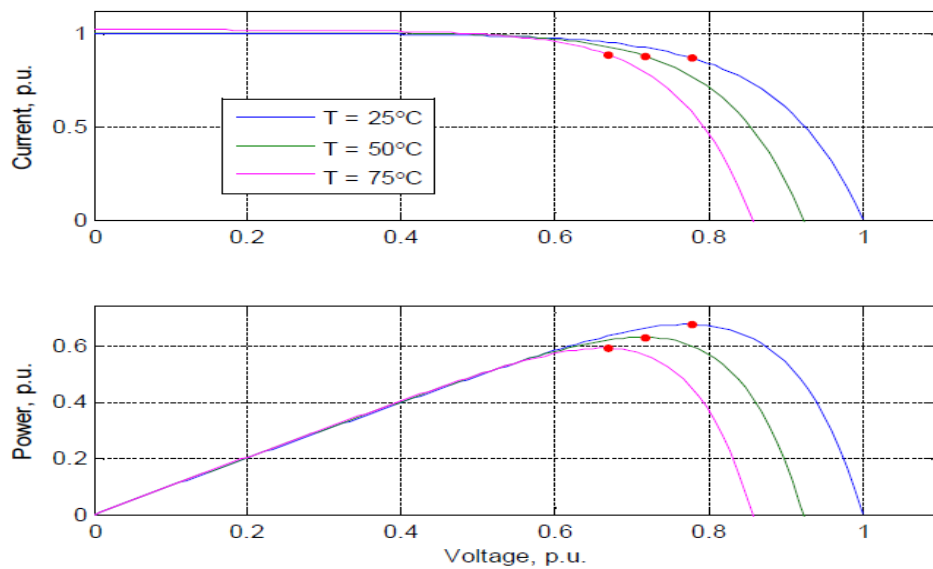


Fig. 6.3 V-I and V-P Curves at Constant Irradiation (1 kW/m²) and Three Different Temperatures

As was mentioned before, the temperature and the irradiation depend on the atmospheric conditions, which are not constant during the year and not even during a single day; they can vary rapidly due to fast changing conditions such as clouds. This causes the MPP to move constantly, depending on the irradiation and temperature conditions. If the operating point is not close to the MPP, great power losses occur.

Hence it is essential to track the MPP in any conditions to assure that the maximum available power is obtained from the PV panel. In a modern solar power converter, this task is entrusted to the MPPT algorithms.

7. DC MOTOR MODEL FOR PV BASED PUMPS

Many PV water pumping systems employ DC motors because they could be directly coupled with PV arrays and make a system very simple. Among different types of DC motors, a permanent magnet DC (PMDC) motor is preferred in PV systems because it can provide higher starting torque. Fig. 6.4 shows an electrical model of a PMDC motor. When the motor is turning, it produces Back EMF (E) which is a voltage proportional to the angular speed of the rotor. From the equivalent circuit, the DC voltage equation for the armature circuit is:

$$V = IR_a + K\omega$$

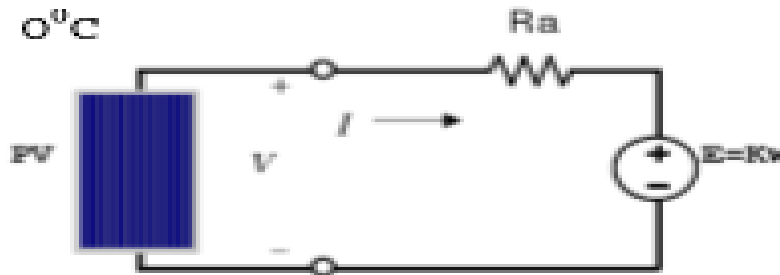


Fig. 6.4 Electrical Model of Permanent Magnet DC Motor

Fig. 6.5 shows a major problem with a direct coupled PV-motor setup in efficiency because of mismatching of operating points. For this example the water pumping system would not start operating until irradiance reaches at $400\text{W}/\text{m}^2$. Once it starts to run, it requires as little as $200\text{W}/\text{m}^2$ of irradiance to maintain the minimum operation. It means that it cannot utilize a fair amount of insolation in the morning.

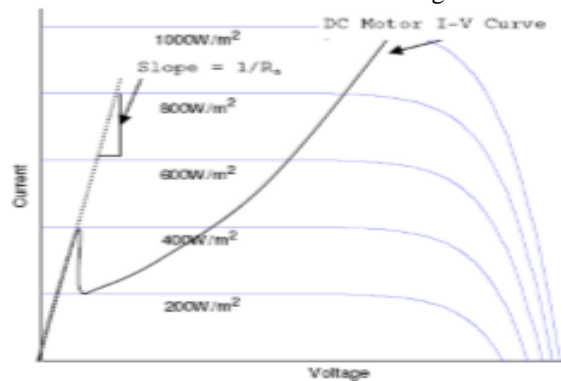


Fig. 6.5 PV I-V Curves with Constant Power Lines (dotted) and a DC motor I-V Curve

Also, when the motor is operated under the locked condition for long time, it may result in shortening of the life of the motor due to input electrical energy converted to heat rather than to mechanical output [5]. To overcome this problem, a MPPT called a linear current booster (LCB) may be used. The MPPT maintains the input voltage and current of LCB at the MPP of PV module. As shown in Figure 10, the power produced at the MPP is relatively low-current and high-voltage which is opposite of those required by the pump motor. The LCB shifts this relationship around and convert into high current and low-voltage power which satisfies the pump motor characteristics. For example, the LCB could start the pump motor as little as $50\text{W}/\text{m}^2$ of irradiance.

Solar water pumps are rated as per voltage supplied and require accessories like filters, float valves, switches, etc to function optimally. Solar pumps are constructed from high quality low lead marine grade bronze and stainless steel and are designed for corrosion-free and maintenance-free service even in harsh environment with long term performance and reliability. Solar pumps are classified into three types according to their applications: submersible, surface, and floating water pumps. A submersible pump draws water from deep wells, and a surface pump draws water from shallow wells, springs, ponds, rivers or tanks, and a floating water pump draws water from reservoirs



with adjusting height ability. The motor and pump are built in together in submersible and floating systems. In the surface system, pump and motor can be selected separately to study the performance of system along with controller and PV panel. A pump produces a unique combination of flow and pressure i.e. high-flow/low-head to low-flow/high-head for a given power input.

Broadly, pumps can be classified under two categories based on operating principle: dynamic pumps and positive displacement pumps. Dynamic pumps operate by developing a high liquid velocity and pressure in a diffusing flow passage. The efficiency of dynamic pumps is lower as compared to positive displacement pumps but have comparatively lower maintenance requirements. Positive-displacement pumps operate by forcing a fixed volume of fluid from the inlet pressure section of the pump into the discharge zone of the pump. These pumps generally tend to be larger than equal-capacity dynamic pumps. Centrifugal pumps and axial flow pumps are dynamic pumps.

8. PERFORMANCE PARAMETERS OF A SOLAR PUMP

The performance of PV water pump mainly depends on the water flow rate which is influenced by weather conditions at the location, especially solar irradiance and air temperature variations. The performance of solar pump depends on the water requirement, size of water storage tank, head (m) by which water has to be lifted, water to be pumped (m^3), PV array virtual energy (kWh), Energy at pump (kWh), unused PV energy (kWh), pump efficiency (%), and system efficiency (%) and diurnal variation in pump pressure due to change in irradiance and pressure compensation [1]. The efficiency of PV technology used in PV generator has also a great influence on the performance. Besides the degradation of PV panels is one of the important parameters which affect the performance of a solar pump.

The performance of solar water pumping system depends on the following parameters:

- Solar radiation availability at the location;
- Total Dynamic Head (TDH): Sum of suction head (height from suction point till pump), discharge head (height from pump to storage inlet) and frictional losses;
- Flow rate of water;
- Total quantity of water requirement; and
- Hydraulic energy: potential energy required in raising the water to discharge level.

9. INDIAN INITIATIVE ON PV PUMPING

India has 26 million ground water pumps in agriculture farms which are run using electricity and diesel. The power failure/ shortage and ever increasing diesel fuel costs affect agriculture production and irrigation of crops. The adoption of solar PV pumps can save considerable electricity and diesel subsidies being provided to farmers. Solar pumping program in India was first started by Ministry of New and Renewable Energy (MNRE) in 1992 and during the 1992– 2014 period, 13,964 solar pumps were installed in the country. With the launch of Jawaharlal Nehru National Solar Mission (JNSSM) in 2010 by MNRE, a fresh thrust has been given to solar pumping program in India under which 3 billion rupees have been allocated as subsidy to be provided to small farmers for the installation of PV pumps. During 2014–15, 17,500 solar-powered pumping systems are to be installed with a target of 1 million solar pumps for irrigation and drinking water purpose by the year 2021. The objective is to boost agricultural yield and reduce dependence on diesel for water pumping in the states including Rajasthan, Tamil Nadu, Andhra Pradesh, Uttar Pradesh, Maharashtra, Chhattisgarh, Madhya Pradesh, Bihar, Punjab, and Himachal Pradesh. The grants to farmers will cover 30% of the cost of solar water pumping system limited to Rs 57,000 per kWp up to 5 kWp PV module capacity for irrigation and other purposes. The participating state governments will have to provide matching grant of at least 15 percent of the cost and the farmer has to bear the remaining cost. Indian government has provided guidelines to the manufacturers of PV panels as per international standards with modern testing procedures, so as to ensure quality product with better performance and long life. Mono/multi-crystalline silicon PV modules as per IEC 61215 specifications or equivalent National or International/ Standards are to be used in solar pumps. The modules must qualify to IEC 61730 Part I and II for safety qualification testing. The efficiency of the PV modules should be minimum 13% and fill factor should be more than 70%. The AC/DC motor pump sets suitable for PV water pumping system and AC–DC, DC–DC converters as per requirement are to be used. This initiative is expected to boost the solar water pumping in India. Similar strategy needs to be followed by other countries especially the developing countries. Bern University of Applied Sciences (BFH) in Switzerland developed a small power (40–120W) photovoltaic water pump which is being produced in Bangalore, India under an International project and is being promoted among women in India for small irrigation.

CONCLUSIONS

A review of current status of solar photovoltaic water pumping system technology research and applications is presented. The study focuses on update on solar water pumping technology, performance analysis studies carried out worldwide, optimum sizing techniques, degradation of PV generator supplying power to pump, economic

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evaluation, environmental aspects and recent advances in materials and efficiency improvement of photovoltaic technology and experience of using solar PV pumps worldwide.

PV water pumping technology is reliable and economically viable alternative to electric and diesel water pumps for irrigation of agriculture crops. PV water pumping for urban, rural and community water supplies and institutions, is another potential feasible sector but is not still widely utilized. The remote inaccessible locations with no grid electricity also need special attention. These sectors still depend on conventional electricity or diesel based pumping system resulting in increased recurring costs to the users. Keeping in view the high installation costs of solar water pumps especially for large irrigation and water supplies, more incentives are required to be provided by governments to make the technology further attractive alternative to diesel and electrical water pumping. Factors affecting the performance and efficiency improving techniques, use of highly efficient PV modules including bifacial modules and degradation of PV generator are areas for further research for lowering the cost, improving the performance and enhancing pumping system life time.

Solar pumping is an attractive alternative for irrigation and rural, urban drinking water pumping applications in developing countries especially India keeping in view huge solar potential and the fact that significant rural population lives in the remote areas which requires water for drinking and irrigation of crops.

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