Review of Solar PV Powered Water Pumping System Using Induction Motor Drive

Akhila V T¹ and Arun S²
¹PG Scholar, Department of Electrical Engineering, Amal Jyothi College of Engineering, Kottayam, India
²Assistant Professor, Department of Electrical Engineering, Amal Jyothi College of Engineering, Kottayam, India
¹akhilavt01@gmail.com ²sarun@amaljyothi.ac.in

Abstract. This paper presents the review of the Solar Photovoltaic (SPV) array fed water pumping system using an Induction Motor Drive (IMD). The penetration of renewable energy powered water pumping systems in industrial and domestic applications receiving wide attention nowadays. The introduction of a three-phase induction motor brings an improved solution to the commercial water pumping system. SPV array fed water pumping system using IMD mainly consist two stages; first stage extracts the maximum power from the solar Photovoltaic (PV) array by restraining the duty ratio of the DC-DC boost converter. In the second stage, a controller is employed to control the switching pulses of the Voltage Source Inverter (VSI). Different control methods are available for regulating IMD like Scalar (V/f control), Direct Torque Control (DTC), Vector control, and DTC use Space Vector PWM (SVPWM) control.

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. DC motor needs frequent maintenance hence AC motors are preferred in most of the pumping applications. Permanent magnet synchronous motors are suitable for the submersible application. Most of the pumping system uses induction motor because it is mechanically simple; having rugged construction and reliable operation. It has low cost, high efficiency, low maintenance than the DC motors and can be used for hazardous and contaminated areas [3].

2. Solar Water Pumping System
Block schematic of solar PV water pumping system is shown in figure 1. Solar panel drives the three-phase induction motor using DC-DC and DC-AC converters. 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].

![Figure 1 Block Diagram of PV Pumping System.](image)

2.1. Design of PV Array
An induction motor of 2.5 kW is selected for the proposed system. If the losses of motor and pump are neglected, the capacity of the PV array should be equivalent to the motor capacity. In this case, a PV array is selected to be of 2.7 kW.

2.2. Design of Voltage Source Inverter
The apparent power rating of VSI is given as,

\[ S_{VSI} = \sqrt{P^2 + Q^2} \]  

(1)

The RMS current through a VSI is given as,

\[ I_{VSI} = \frac{KW \times 10^3}{\sqrt{3} V_m} \]  

(2)

The DC bus voltage of VSI is estimated as,

\[ V_{DC} = \frac{2V_{bus} \cdot \tau}{\sqrt{3}} \]  

(3)
Open loop V/f control can be used for low power water pumping systems.

2.3. Design of Centrifugal Water Pump

The Centrifugal water pump is designed using its torque-speed relationship as,

\[ T_p = Kw^2 \]

Where K is the proportionality constant, w is the angular velocity and \( T_p \) is the torque.

3. Control Methods of IMD for SPV Water Pumping System

3.1. Scalar Control (V/f Control)

A simple V/f approach is used to control IMD in [8] [9] but this approach suffers from DC link voltage instability. However, V/f control is simple, easy to implement and cost-effective. The direct torque control and vector control approaches are complicated and they require extra current sensors for implementation. In V/f control, only DC bus voltage, PV current, and voltage are sensed. The system tracks the maximum power point by varying the modulation frequency so that the IMD is able to extract the maximum power from the solar PV array at sustained torque for various solar insolations. By utilizing V/f control, the starting behavior of the IMD is improved even IMD is started with lower solar irradiation level. Hence, it is likely to pump water from morning to till the evening. The starting current of the induction motor connected to the fixed voltage AC mains is approximately 5 to 6 times of full load current [3]. Thus, large numbers of solar modules are required to start the motor without any control. A tranquil starting of the induction motor is feasible by using V/f control without drawing high starting current. Figure 2 shows the block schematic of scalar control.

A disadvantage of scalar control is that the torque developed is load dependent as it is not controlled directly. Also, the transient response of such a control is not rapid due to the predefined switching pattern of the inverter. However, if there is a contiguous block to the rotor rotation, it will lead to heating of the motor in spite of the functioning of the over current control loop. By means of a speed/position sensor, the problem relating to the blocked rotor and the load-dependent speed can be overcome [8]. However, this will add to the system cost, size, and complexity.

3.2. Vector Control

The scalar control of IMD gives a sluggish response and it can avoid using vector control [10]. This control is also known as the “field oriented control”, “flux oriented control” or “indirect torque control”. The field-oriented control performs the Clarke-Park transformation, which converts three phase vectors to a two-dimensional rotating reference frame (d-q). The “d” component stands for the flux producing component and the “q” component symbolize the torque producing component. These two decoupled components can be individually controlled by passing through separate PI controllers. The outputs of the PI controllers are transformed back to the three-dimensional stationary reference plane using the inverse of the Clarke-Park transformation.
Depending on the measurement method, the vector control is grouped into two subcategories: direct and indirect vector control. Indirect vector control, the flux measurement is done by employing flux sensing coils or the Hall devices. It will cause additional hardware cost and in addition, measurement is not highly accurate. Hence, this method is not a very good control technique. The most common method is indirect vector control. In this method, the flux angle is measured indirectly but is estimated from the equivalent circuit model and from measurements of the rotor speed, the stator current, and the voltage. One common technique for determining the rotor flux is based on the slip relation. This needs the measurement of the rotor position and the stator current. With current and position sensors, this method performs reasonably well over the full speed range.

3.3. Direct Torque Control (DTC)

The difference between the traditional vector control and the DTC is that it has no fixed switching pattern. The inverter switched by the DTC according to the load needs. Due to the elimination of the fixed switching pattern (characteristic of the vector and the scalar control), the DTC response is extremely fast during the instant load changes. Decoupled control of torque and flux, the absence of mechanical transducers, having low computational time, reduced parameter sensitivity, and very simple control scheme are the main features of DTC [11]. In simple DTC control current regulator, PWM pulse generation, PI control of flux and torque, and coordinate transformation are not required. In this method, one nonzero and two zero voltage vectors of the inverter are selected for the operation. The vectors are selected based on the instantaneous errors in torque and stator flux magnitude. The block diagram of DTC control is shown in figure 3.

3.3.1. DTC Using SVPWM. As compared to the Sinusoidal Pulse Width Modulation (SPWM) space vector control has the advantages like reduced switching frequency, low current ripples, and good utilization of DC bus voltages [12]. Based on instantaneous current and voltage measurements it is possible to calculate the voltage required to drive the current output torque and stator flux to the necessitated values within fixed time duration. This computed voltage then synthesized using space vector modulation. The instantaneous stator flux and output torque can be estimated by using the applied voltage and motor current. The estimated values are used to calculate the required change in output torque and stator flux. The back EMF can be determined from the stator flux and current. The voltage required to achieve the changes in stator current can be calculated knowing the back EMF of the motor and the changes in the torques corresponds to the changes in stator current. The block schematic of SVPWM is shown in figure 4.
SVPWM [13][14]. Space vector modulation method is suitable for variable speed applications. The triggering pulses for the inverter switches are developed using this control strategy. This method gives the higher magnitude of the fundamental output voltage and lowers harmonic distortion as compared to SPWM technique. The steps involved in SVPWM method is given below.

STEP 1: Co-ordinate Transformation:
Consider a three-phase two level Voltage Source Inverter (VSI) as shown in figure 5. The voltage $e_a$, $e_b$, and $e_c$ are the output voltages applied to the winding of the motor. $S_1$ through $S_6$ are the six power switches which are controlled by $a$, $b$, $c$, $a'$, $b'$, and $c'$ gating signals. There are eight possible combinations of on and off states for the three upper power switches.

The relationship between the switching variable vector $[a, b, c]$, phase voltages $[V_a, V_b, V_c]$ and the line-to-line voltage vector $[V_{ab}, V_{bc}, V_{ca}]$ is given in the following Table 1. The phase voltages corresponding to the eight combinations of switching pattern can be mapped into the d-q plane by using d-q transformation as shown in Table II. This mapping results in six non-zero vectors and two zero vectors. The d-q transformation can be applied to the reference $a$, $b$, and $c$ voltages to obtain the reference $V_{out}$ in the d-q plane as shown in figure 6.

STEP 2: Sector Determination and Time Period Calculation:
It is necessary to know in which sector the output voltage is located to determine the switching time periods and switching sequence. By judging the value of the phase angle of space vector $V_{out}$, the sector number can be determined. The output voltage $V_{out}$ can be in any one of sector 1 to sector 6 and it is approximated by switching between the two non-zero basic vectors that border the sector of
the current output voltage. If $V_{out}$ is in Sector1, it can be approximated by switching the inverter between states $V1$ and $V2$ for a time period of $T1$ and $T2$ respectively. Because the sum of $T2$ and $T1$ should be less than or equal to $T_{pwm}$, the inverter should remain in $T0$ or $T7$ for the rest of the period.

**STEP 3: Switching Pattern Generation:**

The symmetric space vector PWM switching pattern is a better and conventionally used switching pattern. As the name indicates, it is symmetric pulsation and both zero vectors are applied in this method and it is shown in figure 7.

Table 1 Switching States and Output Voltage of VSI.

| A | b | c | $V_a$ | $V_b$ | $V_c$ | $V_{ab}$ | $V_{bc}$ | $V_{ca}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | $2/3$ | $-1/3$ | $-1/3$ | 1 | 0 | $-1$ |
| 1 | 1 | 0 | $1/3$ | $1/3$ | $2/3$ | 0 | 1 | $-1$ |
| 0 | 1 | 0 | $-1/3$ | $2/3$ | $-1/3$ | $-1$ | 1 | 0 |
| 0 | 1 | 1 | $-2/3$ | $1/3$ | $1/3$ | $-1$ | 0 | 1 |
| 0 | 0 | 1 | $-1/3$ | $-1/3$ | $2/3$ | 0 | $-1$ | 1 |
| 1 | 0 | 1 | $1/3$ | $-2/3$ | $1/3$ | $1$ | $-1$ | 0 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

4. **Comparison**

The induction motor control methods can be classified in to three; scalar control, vector control and direct torque control. The scalar control methods have the advantages like simple implementation, sensorless operation and simple control strategy. It is also known as $V/f$ control. The scalar controlled induction motor provides sluggish response that is the main short coming of this method and it more suitable for low performance drives.
The vector controlled method which is also known as field-oriented control (FOC) provides decoupled control of flux and torque. These methods have the control similar to that of separately excited DC motor. The presence of reference frame transformation makes the implementation of FOC is complex as compared with other methods. DTC or direct self-control (DSF) is a sensorless type control and by using this control it is possible to obtain good dynamic control without any mechanical transducers on the machine shaft. The conventional DTC is preferable in the high power range applications. Compared to FOC, DTC does not require any PWM signal generator, coordinate transformation, and current regulator. DTC has the advantages of the simplicity of operation, good torque control in steady state and transient operating conditions and it is less sensitive to the parameter variation in comparison with FOC. In DTC based scheme the control of torque and flux at very low speed is difficult. In conventional DTC method, direct torque control can be achieved but the direct current control is absent [15].

4.1. Comparison of DTC methods

| Properties             | Simple DTC Control | DTC using SVPWM |
|------------------------|--------------------|-----------------|
| Current Distortion     | High               | Low             |
| Torque Ripple          | High               | Low             |
| Switching Frequency    | Change with motor speed | Constant       |
| Position or Speed Sensor | Not required       | Not required    |
| Torque Response        | Fast               | Fast            |
| Control Method         | Relatively simple  | Very complex    |

5. Conclusion

Different control methods of the induction motor are reviewed. Scalar control of IMD provides a sluggish response but its implementation is simple compared to others. The decoupled control of flux and torque is the main attractiveness of FOC. Both V/f control and vector control have fixed switching pattern while DTC using space vector control have varying switching pattern and it provides simple direct control of torque. In DTC method, the ripples in flux, torque, and current are high which can be reduced by employing SVPWM. Scalar control methods are more preferred for a low-performance drive and vector control is preferred for variable frequency application. The DTC method is suitable for high power range applications. The detailed comparison of DTC scheme is described in this paper.

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