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Comprehensive Review on Solar Water Pumping System for Irrigation Application

Abstract: - In India, traditionally water pumps are powered by diesel, electricity or gasoline. Traditional water pumps are more widely available and have low initial cost. However, solar water pumps are becoming popular in irrigation work and rural areas due to their ability to reduce electricity bills, eco-friendly nature and also eliminate the need of other fossil fuel. Moreover, solar water pumping system enable the farmers to start their irrigation process at any time without depending on utility grid. Also, it generates the revenue to enhance the financial condition of farmers. To further improve the performance of solar water pumping system, this paper presents the detail overview of different types of solar water pumping system utilized by the researchers. The detail review about different types of motor, converter system and types of control techniques is presented. A comparative analysis of different types of motors is carried out in detail.

Keywords: Water Pumps, Permanent Magnet Synchronous Motor (PMSM), Field Oriented Control (FOC), Maximum Power Point Tracking (MPPT), Bi-directional Converter

I. INTRODUCTION

Growing demand of electrical energy due to rapidly increasing population, depletion of conventional energy sources, abrupt climate change, global warming, are the menace of today's world [1]. The ultimate panacea for dealing with these problems appears to be renewable energy Therefore, for the sustainable development and reducing the environmental impact caused by conventional energy sources, small power generators based on renewable energy sources are integrated with the national grid [1]. Owing to its merits of pollution-free nature, noiseless operation, abundant availability, and reducing installation cost, the solar photovoltaic (PV) energy is one of the best forms of renewable energy. With the advancement of semiconductor technology, the steadfast improvement in PV array technology has improved its efficiency and effectiveness. Especially, it has proved to be a vanguard in supplying power to far-flung areas where transmission network cannot reach [1]. Moreover, the benefits of using PV array power include its easy installation, low maintenance requirement, and many more. Amongst various sectors where solar PV energy is being utilized, water pumping for domestic as well as irrigation purposes is seemingly one of the best and economically viable applications of PV energy generating system [1].

In past, electric drives such as a dc motor and an induction motor have been used for the purpose of water pumping but they suffer various problems [2]. The presence of brushes and commutator in dc motor increase the maintenance problems [2]. In case of an induction motor drive, the stator current consists of magnetizing as well as torque producing components [2]. The absence of brushes and commutator in Permanent Magnet Synchronous Motor (PMSM) reduces the maintenance problems. The presence of permanent magnet in PMSM eliminates the need of magnetizing current and the stator only requires the torque producing component [2]. Hence, for the same power rating PMSM operates at high power factor as well as at increased efficiency as compared to induction

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motor drive [2]. Thus, PMSM drive offers high efficiency, power factor, power density and good dynamic performance.

The SPV (Solar Photo Voltaic) array converts the energy from sunlight into electrical energy. This electrical energy is fed to DC – DC boost converter. The boost converter adjusts the SPV array voltage by adjusting the duty ratio in such a way that SPV array voltage settles at MPP voltage. This output power of the boost converter is fed to the VSI [3]. The VSI processes this power and drives the motor. The Motor converts the electrical energy into mechanical rotating energy. The Motor is coupled to a pump. The rotation of Motor rotates the pump and water pumping operation is realized [3].

According to the applications, Various isolated and nonisolated configuration of PCU's (Power Converter Units) is presented in literature. The application of nonisolated converters is advantageous as it involves: less design complexity, cheaper cost, and easy implementation. However, isolated converters are reliable with elevated cost, and limited power handling capability [4].

To utilize maximum efficiency of PV integrated system, maximum power point tracking (MPPT) techniques are needed. Numerous MPPT techniques are already present in the existing literature [5]. Perturb and observe (P&O) and incremental conductance (INC) are widely used MPPT techniques among all [5]. Many other methods based on optimization technique such as genetic algorithm, neural network, particle swarm optimization, fuzzy logic, grey wolf optimization, etc. have been proposed and they also possess excellent tracking efficiency [3].

I. CONCEPTUAL BACKGROUND

The agriculture sector is one of the major contributors of Gross Domestic Product (GDP) of India, Due to uncertainty of rainfall across India, the contribution of agriculture in GDP is decreasing day by day. To meet the demand for water, more than twenty million water pumps are installed in the country, consuming about 92 billion units of energy annually (22% of the country's electricity consumption). Most of the energy consumed to meet this water demand (67 billion units out of 92 billion units) is generated with fossil fuels. Conventional WPS (Water Pumping System) powered by energy generated from fossil fuels which leads to CO2 emission and global warming. Photovoltaic water pumping systems can be classified into two broad categories: (i) direct conversion systems, and (ii) solar thermal or thermodynamic system. The direct conversion system directly converts solar energy to electrical energy for running motors and pumps. The working substance used in solar thermal or thermodynamic system pumps is pentane — an organic fluid having low boiling point. Even though the thermodynamic system has a low cost of operation, but its maintenance cost is high [6].

There is a huge potential to generate energy from renewable energy source like solar, wind, biomass, hydro etc. As per latest development in India, total of 417 GW installed capacity is provided in 2023 [7]. However, total of 67 GW power generation is provided using solar energy. Moreover, the various government schemes also motivate to install solar panel in domestic and irrigation application. Also, integration of solar power generation system with the national grid results in reduction of overall energy utilization cost. There are lots of application where solar power helps to reduce the overall cost of application. The major focus of this paper is incline towards solar powered water pumping system which will helps farmers to provide water pumping system at any time as well as gain some financial stability by providing the power to the grid.

Basic block diagram of solar water pumping system is shown in figure-1 [8]. It consists of solar PV array, DC to DC converter, DC to AC converter and Motor drive system. Also, for bidirectional power flow, front end converter is connected in parallel with solar water pumping system. Power generated from solar PV array to supplied to the DC-to-DC converter where the DC voltage is adjusted as per requirement of water pumping system. MPPT algorithm is employed to extract the maximum power from the solar PV array. The output power from the DC-to-DC converter is fed to the 3-phase inverter. The main function of 3-phase inverter is to control the speed of motor such that water pumping system work efficiently and overall performance of solar water pumping system is improved. For the smooth control of motor parameters, field-oriented control (FOC) is implemented in closed loop control structure of inverter.

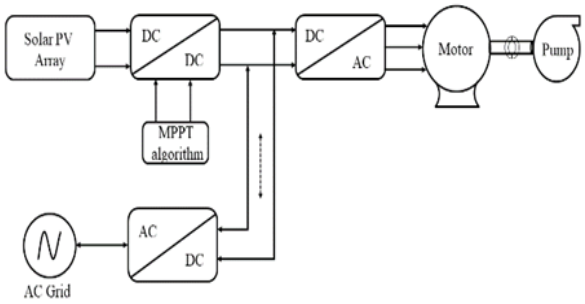

Fig.1 Block diagram of solar water pumping system

Also, as solar irradiation is uncertain and also there is need of water pumping for particular time in agriculture application. There is need of bidirectional power flow between the utility grid and Solar PV array. For the bidirectional power flow, front end converter (FEC) is used in parallel with the main system. The output of DC-to-DC converter is also connected to the input of the front-end converter so that as and when water pumping system is not available, power generated from the solar is feed back to the grid through front end converter. Moreover, there is also provision to take the power from the grid when solar power output is not available to drive the water pumping system.

The direct driven solar water pumping system is considered as it is simple in design, does not required energy storage system like battery and thus also entire system is less costly and free from maintenance of energy storage device. A Single stage and two stage topologies are the most common topologies used in solar powered water pumping applications. The traditional two-stage topology uses the first stage to extract maximum power from the PV array and the second stage to keep the DC link voltage constant. A single stage topology, on the other hand, is preferred because the DC-DC converter in the first stage is fully removed [8].

II. MOTOR CONFIGURATION

The most important component of water pump applications are motors and pumps. In practice, different motors are used depending on supply, availability and cost [4]. However, their selection depends on power, efficiency, cost and availability [4]. The classification of motor types used in most of the water pumping system is as mention below. The motor can be broadly classified as AC motor and DC motor. The conventional DC motor with brushes increase maintenance cost and also it is less sturdy and trustworthy. These stated limitations can be overcome by bring in BLDC motor (Brushless DC Motor). The most attractive thing regarding DC motor is that it eliminates conversion losses as it is directly fed from solar PV array [4].

Figure-2 shows the list of motor preferred for water pumping system. These motors are mostly preferred as it has its own advantages for solar water pumping system and it makes overall solar water pumping system efficient.

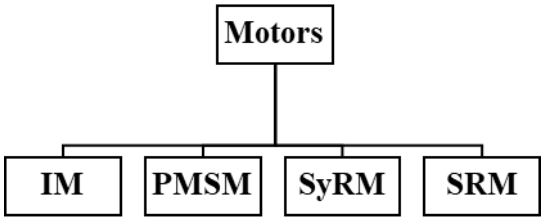

Fig. 2 List of motors preferred for SWP system

A. *IM based Solar Water Pumping System*

IM is a popular choice for water pumping due to its low cost, robust construction, easy availability in the local market, low maintenance, and inherent short circuit protection 9]. For the speed control of IM, scalar or vector control technique is most preferable [9]. But, due to its low torque to power density ration, and high noise, IM is

little-bit costlier choice for water pumping system. Also, efficiency of IM for water pumping system is very low as compared to PMSM and BLDC motor available in the market.

B. *PMSM based Solar Water Pumping System*

The PMSM has advantage of high efficiency, lower torque ripple [9], compact design, high torque to inertia ratio, quick acceleration and deceleration capability, high air-gap flux density and high-power factor which is suited for water pumping system. Therefore, PMSM is one of the best choices for solar water pumping system.

C. *SyRM (Synchronous Reluctance Motor) based Solar Water Pumping System*

The SyRM offers the degree of freedom in torque production by virtue of its construction. SyRM drive is robust, simple to control and highly efficient for water pumping system [9]. Therefore, the SyRM has low cost and higher efficiency than the other AC motors.

D. *SRM based Solar Water Pumping System*

Due to the critical nature of the water pump application, there is a need to use a robust, highly reliable, cost-effective motor drive with high starting torque and efficiency [10]. SRM provide high reliability, cost effectiveness and high starting torque. But, SRM has low power density, controllability and high noise which makes it difficult for solar water pumping system.

Thus, looking at the all criteria for selection of motor for water pumping system, it seems that as PMSM has high efficiency, power density, high torque, good controllability and reliability with less maintenance Which makes PMSM as the best choice for solar water pumping system.

Table I

Comparison of different motors

Criteria	**IM**	**PMSM**	**SyRM**	**SRM**
Power density	3.5	5	5	3.5
Torque	3	5	4	4
Efficiency	3.5	5	5	3.5
Controllability	5	4	3	3
Reliability	5	4	5	5
Cost	5	3	3	4
Maintenance	5	4	5	3
Noise	4	3.5	4	3

III. CONVERTER TOPOLOGY

One of the vital components of solar water pumping system is power converter. The converter controls voltage level as Solar PV cell characteristic is nonlinear in nature. Thus, to provide suitable voltage and power for solar water pumping system Converter plays vital role of controlling voltage level and also useful for grid interfacing and power factor correction.

This power converter can be either isolated or non-isolated converter. The use of non-isolated converters is advantageous because it involves less design complexity, lower cost, and ease of implementation. However, isolated converters are reliable, cost a lot of money, and have limited power handling capacity.

Figure 3 shows block diagram for multi stage SPWPS (Solar Photovoltaic Water Pumping System). Multi stage SPWPS includes DC to DC converter, the motor driver, Motor, the control strategy for DC-to-DC converter, control strategy for motor driver and sensor inputs [9].

The first stage is for tracking the maximum power from the PV solar source, and typically a high gain converter DC-DC is used to boost the PV voltage. The second stage is for motor control and is specific to the motor used for pumping. The motor which can be used for water pumping are IM, BLDC motor, PMSM, SyRM and SRM.

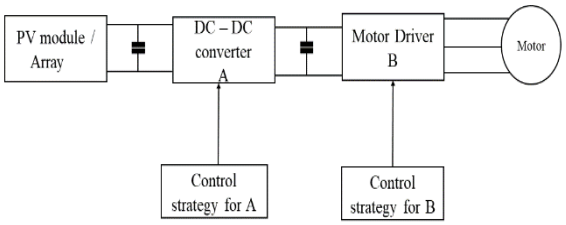

Fig. 3 Multistage solar photo-voltaic water pumping system [9]

The proposed system consists of an extended topology of boost DC-DC converter with MPPT to extract maximum available power from SPV array [8]. The PMSM is used for water pumping and is controlled and driven by voltage source inverter. A perturb and observer MPPT algorithm control the duty ratio of the converter and extract the maximum energy from the PV array. A Sine PWM based Field Oriented Control technique is implemented for driving the PMSM coupled water pumping system [8]. Unit Vector control Theory (UVT) is used for the bidirectional power flow between utility grid and solar pv array feeding power to water pumping system.

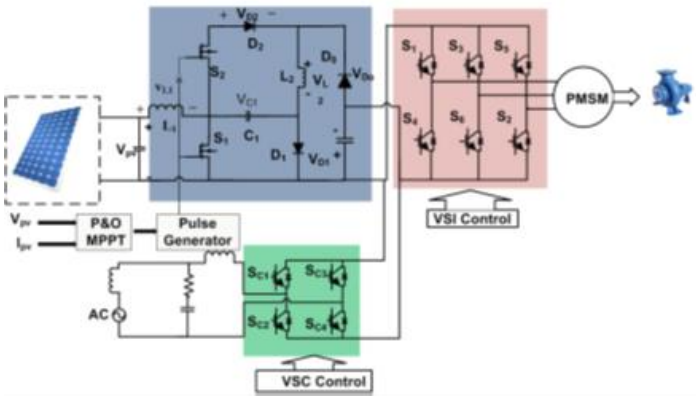

Fig. 4 Circuit configuration of water pumping system based on PMSM drive [8]

The proposed system uses Incremental conductance technique for MPPT to increase energy transfer capability of Solar PV array. The scalar control technique eliminates use of speed sensor or encoder. Also, it uses IM drive for solar water pumping [11].

A new simplified space vector modulated direct torque control (SVM-DTC) method for induction motor drive is used in solar water pumping system [12]. An effective power sharing between grid and photovoltaic array is proposed. The incremental conductance technique is preferred to extract maximum power from PV array [12].

An incremental conductance (INC) based maximum power point tracking (MPPT) control technique is utilized which will control duty ratio [13]. A scalar control voltage source inverter is used to drive Induction Motor for water pumping system. A scalar control abolishes the need of speed sensor/encoder [13].

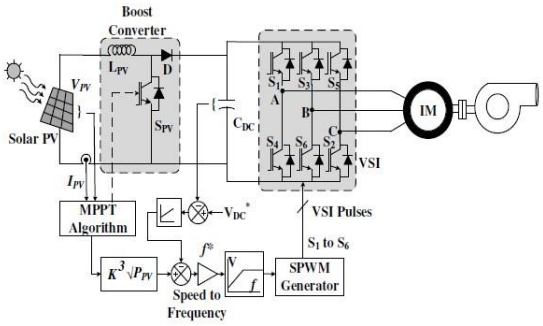

Fig. 5 IM drive based proposed water pumping system [13]

The proposed system comprises of a solar PV array, a boost converter for maximum power point tracking (MPPT), a voltage source inverter to drive the motor, another boost converter for power factor correction (PFC) and a PMSM coupled to a pump. The speed of the PMSM is regulated using sensor-less vector control technique [14].

The proposed work uses a sensorless speed and position estimation for speed control of PMSM [5]. The estimation of rotor speed and position, is achieved through the estimation of stator flux from voltages and currents in stationary reference frame. As the conventional flux estimators suffer from the problems such as saturation, DC drift and distortion, this work proposes a mix multi-resonant structure for flux estimation. A sensorless speed control decreases the cost and improves the reliability of the solar water pumping (SWP) system [5].

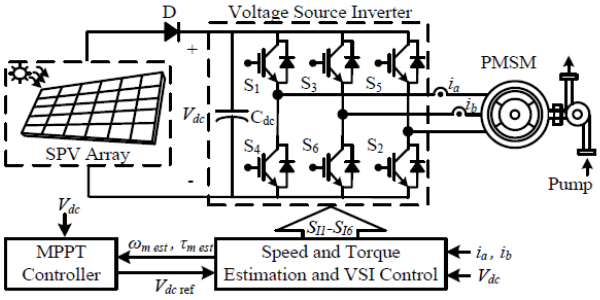

Fig. 6 Reduced sensor based water pumping system [5]

Battery energy storage is utilized to get competent and dependable solar photovoltaic powered water pumping system [10]. The bidirectional DC-DC converter is used to get maximum energy from solar PV and also provide charging/discharging control of battery energy storage. The switched reluctance motor drive for solar water pumping is used as SRM provides high starting torque, cost effectiveness and highly dependable motor. The optimization of PV array is achieved by perturb and observer algorithm [10].

An improved perturb and observe (P&O) algorithm with variable step size is proposed which allows maximum power tracking during rapid change in irradiation, decrease steady state PV power swing and shield Induction motor against load drop [15]. predictive torque and flow control (PTC) is used to control the IM drive because of its benefits such as quick torque response, lower torque ripple, and ease of implementation. The fuzzy logic controller is utilized to control dc link voltage [15].

In proposed system inverter-fed PMSM drive the water pump and it is controlled with conventional Field - Oriented Control scheme. The PV array is directly connected to the DC bus of VSI without any intermediate power conversion stage [16].

IV. BIDIRECTIONAL POWER FLOW

The bidirectional power flow between utility grid and DC link of solar water pumping system provides extra source of income when water pumping is not required and also provide uninterrupted power under uncertain changing weather conditions.

The Solar PV is used to fed power to utility grid when water pumping is not required and during low solar insolation level is not sufficient, utility grid provide uninterrupted power for water pumping through common dc link [1]. The unit vector template theory is used to generate switching pulses for VSC which controls the bidirectional power flow between utility grid and solar PV system.

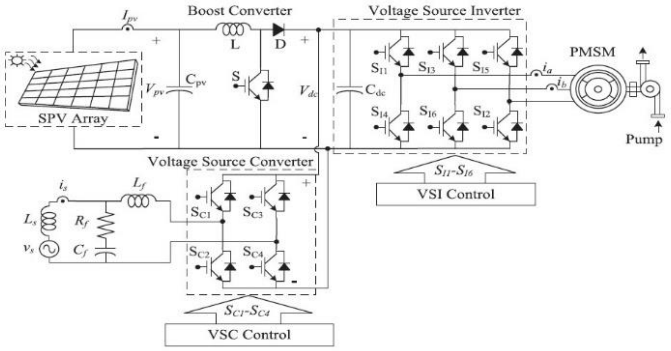

Fig.7 Proposed water pumping system using PMSM drive [1]

The bidirectional power flow in between the DC link is achieved using unit vector control theory which allows to operate motor at its rated capacity in spite of uncertain weather condition and also provide competent utilization of available power [8].

A new simplified space vector modulated direct torque control (SVM-DTC) method for induction motor drive is used in solar water pumping system for agricultural and irrigational loads is proposed [12]and also it provide smart sharing of power between grid and solar photovoltaic array. A modified INC-MPPT with the variable step size is proposed to extract maximum power from Solar PV array [12].

The proposed system provides smart power sharing between the two power sources [17]. The maximum energy from Solar PV is utilized and given priority over the grid power as it provides minimum cost. This can be achieved by two boost converter, DBR (Diode Bridge Rectifier) , DC link capacitor. PFC (Power Factor Correction) boost converter also maintain THD of AC mains current under specified limits [17].

In the proposed system, the boost converter facilitates the transfer of peak power from the Solar PV array to the IMD. While the VSI is the vital component which is used to drive the IMD. A grid connected VSC transfers the power between grid and the DC link. Moreover, the VSC boosts the DC link voltage and improves the power quality at the AC mains [18].

A single-phase voltage source converter with unit vector template approach enables bidirectional power flow between grid and DC bus of voltage source inverter which is connected to BLDC motor [19]. In proposed system when water pumping is not required power flow from Solar PV array to the grid and if sufficient power is not available from solar PV array, then power flow form grid to the BLDC motor pump to run pump at its prescribed capacity [19].

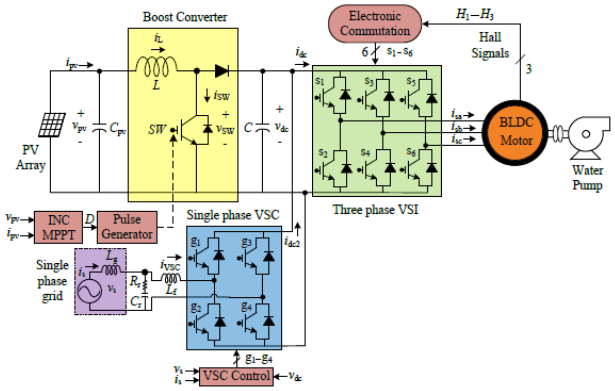

Fig.8 water pumping system based on BLDC drive [19]

The single stage solar water pumping system with SRM drive is used with efficient control technique. Single stage technique without common dc link capacitor is used which eliminate need of large size dc link capacitor [20]. The proposed scheme is used for all four modes of operation using SRM drive and improved control technique which is used for bidirectional power flow between solar PV array and utility grid [20].

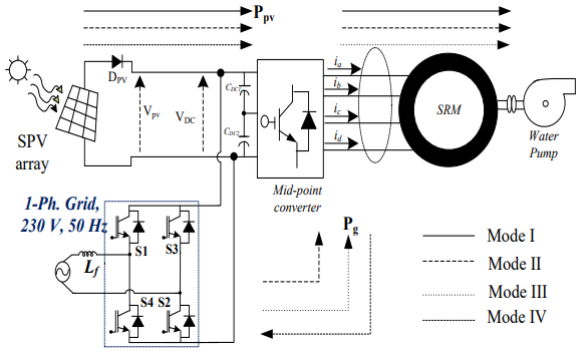

Fig. 9 solar water pumping system using SRM drive [20]

CONCLUSION

This paper presented the detailed review about the solar water pumping system for irrigation application. The various types of solar water pumping system are analyzed. The detail comparative analysis of different types of motor employed in the solar water pumping system is presented. The different control technique used to control the power flow in the complete solar water pumping system is analyzed. The various converter topology is reviewed in details for enhancing the performance for solar water pumping system. The bi-directional power flow system is also presented. The solar water pumping system with bi-directional power flow system will provide the better utilization of complete system with increasing the financial condition of users. It is observed

that amongst the all types of motor configuration, solar water pumping system with PMSM drive is best suitable for higher efficiency with lower cost of operation.

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