

## Comprehensive Review On Solar Induction Motor Water Pumping System For Irrigation Application

<sup>1</sup>Wissam niyazi Mustafa, <sup>2</sup>Zaki M. Abdullah , <sup>3</sup>Bilal Abdullah Nasir

<sup>1</sup>Karkuk Technical College, Northern Technical University email:  
wissam.niyazi24msc@ntu.edu.iq

<sup>2</sup>Hawija Technical College, Northern Technical University email: drzaki\_hwj@ntu.edu.iq

<sup>3</sup>Polytechnic College Hawija, Northern Technical University, Hawija, 36007, Iraq. email:  
bilalalnasir@ntu.edu.iq

**Abstract:** - 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 and using induction in water pumping .

Due to insufficient electricity and soaring diesel costs, solar energy based water pumping system has emerged as a promising alternative to the conventional electricity and diesel based pumping systems used in rural, urban and remote regions to pump water for community water supplies and irrigation. Solar water pump works on electricity generated using photovoltaic (PV) technology. The PV technology converts solar energy into electrical energy to run a DC or AC motor based water pump. This paper presents a comprehensive review of solar energy based water pumping system and technology including its historical background and principle of its functioning, various physical components and classification, parameters, such as environmental conditions and photovoltaic materials that has an effect on the overall performance of the system. Emphasis has been made on induction motor based solar pumping systems and their control methodologies including their advantages as well as disadvantages and future scopes in solar water pumping systems.

### 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 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].

Non-reliability in availability of electricity, particularly in developing countries and in rural areas, and increase in diesel prices, it is essential to have other alternative water pumping technologies. Solar water pumping system has gained increasing popularity in this regard because it reduces dependence on electricity generated from diesel, gas or coal[1]. Photovoltaic (PV) technology is seen as technology of the future for generation of distributed low-power electricity. Solar-powered pumps are fueled by electricity generated by PV panels or by the emitted thermal energy available from collected sunlight[2]. Solar powered PV pumps is cost effective because of low operation and maintenance costs and is also more environmental friendly as compared to pumps powered by an internal combustion engine (ICE). Moreover, one of its most attractive features is the ease of increasing installed power by just increasing the number of panels. PV system consists of PV modules, which comprise of PV cells that directly convert solar energy into direct current (DC) electricity. There is considerable scope for utilization of PV pumping systems for supplying water in rural as well as urban areas including agricultural and industrial water requirements. As water is stored in reservoirs to be used according to energy requirement, similarly PV pump storage system stores solar energy when sunlight is available so that it can be used as per demands. Many experimental DC motor driven PV pumps in use in several parts of the world have maintenance problems due to the presence of commutator and brushes. Hence, where reliable and maintenance free operation at minimum cost is a necessity, induction motor based on pumping system can be popular.

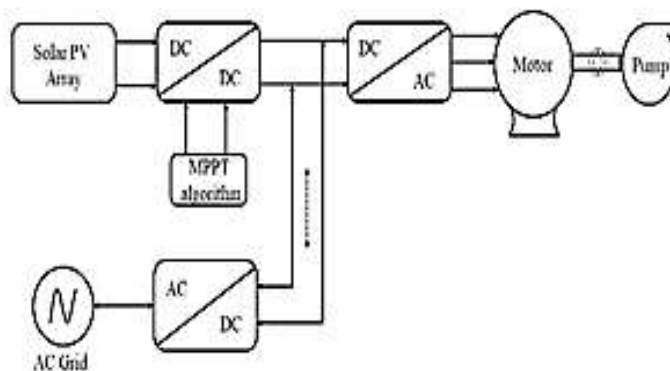
## **II. CONCEPTUAL BACKGROUND**

The agriculture sector is one of the major contributors of Gross Domestic Product (GDP), Due to uncertainty of rainfall , the contribution of agriculture in GDP is decreasing day by day. To meet the demand for water, more than ten's million water pumps are installed in the word, consuming about tens billion units of energy annually (22% of the word 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 CO<sub>2</sub> 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 the world, total of hundreds 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.

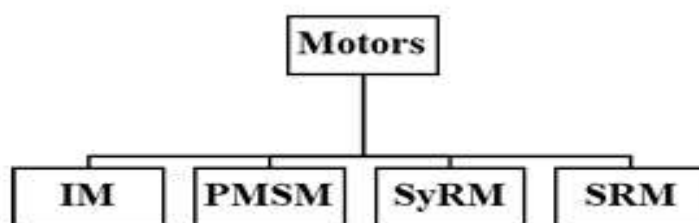
The direct driven solar water pumping system is considered as it is simple in design, does not required energy storage system like battery and thus also entire system is less costly and free from maintenance of energy storage device. A Single stage and two stage topologies are the most common topologies 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].

### III. 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 3-phase induction motor has high efficiency, power density, high torque, good controllability and reliability with less maintenance Which makes 3-phase induction motor as the best choice for solar water pumping system.

## IV. FUNCTIONING OF SOLAR WATER PUMPING SYSTEM

A typical solar powered water pumping system consists of a PV array/module, controllers (pump and batteries), converter and/or inverters, motor, pumping system and storage tank. Fig. 1 is a schematic representative of a simple solar powered water pumping system and Fig.2 shows the various components of the pumping system in detail.

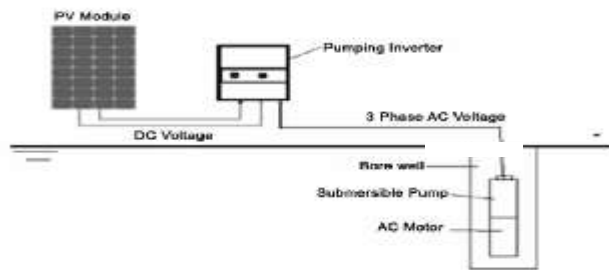


Fig. 1. Schematic of solar powered water pumping system.

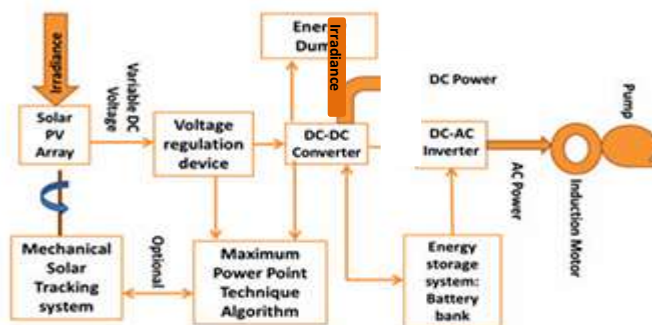


**Fig. 2. Components of solar powered water pumping system.**

The photovoltaic module operation depends strongly on the load characteristics to which it is connected. Indeed, for a load, with an internal resistance  $R_i$ , the optimal adaptation occurs only at one particular operating point, called Maximum Power Point (MPP) and is referred to as  $P_{max}$  and at this point photovoltaic system operates more efficiently. Thus, when the source and the load are connected directly then the output of the PV module is rarely maximum and the operating point is never optimal. To overcome this problem, addition of an adaptation device, MPPT controller with a DC-DC converter, between the source and the load is required. So, the MPPT controller is also required to track the new modified maximum power point in its corresponding curve.

The maximum power point tracking (MPPT) controller will ensure that the PV array always works at the highest efficiency despite very optimal load requirements [6]. MPPT is an electronic system that utilizes the PV module in a manner that it produces power to their maximum capability [7]. MPPT is an electronic system that keeps changing the electronic point on the modules instead of physically moving them in the direction of the sun, so that the modules are able to deliver maximum available power. MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different. The extra power generated is then made available as increased battery charge current. As the PV pumping systems are expensive, it should always run at MPPT to extract the best performance. But the power generated from the PV modules keeps varying; therefore, it is necessary to match the load requirements with the maximum power generation [8]. Pulse Width Modulation (PWM) is another controller technique which is used in PV pumping systems. In PWM, the output voltage is controlled by modifying the pulse – width thereby maintaining the output load.

The DC power generated by PV modules need to be converted to a specified form using Power Conditioning Unit (PCU). The PCU can either be a converter or an inverter depending on the PV system application. As the number of PCUs and two – level voltage outputs increase, the power losses and the ripple content in the motor current increases respectively [9]. A single PCU and more than two – level voltage output will be advantageous in the PV system.

Equations 1 – 5 describe the standard equations for solar powered PV models.

- 1)  $I_{pv} = I_1 - I_0 \left[ \exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{AKT}\right) - 1 \right] - \frac{V_{pv} + I_{pv}R_s}{R_{SH}}$
- 2)  $P_{pv} = V_{pv} * I_{pv}$
- 3)  $P_{max} = I_{sc} * V_{oc}$
- 4)  $V_{oc} = \frac{KT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \cong \frac{KT}{q} \ln\left(\frac{I_L}{I_0}\right)$
- 5)  $\eta_c = \eta_{ref} [1 - \beta_{ref}(T_c - T_{ref}) + \gamma \log_{10} I(t)]$

where,  $I$  is the current,  $V$  refers to voltage,  $T$  refers to temperature,  $ref$  refers to temperature coefficient,  $\gamma$  is the solar irradiance coefficient,  $P$  refers to power,  $R$  is the resistance,  $k$  is the Boltzmann constant,  $q$  is the electron charge and is the diode ideality factor.

#### **A. Storage based PV water pumping systems**

The electricity generated from the PV system can either be stored in battery coupled systems, or can be used to run the pump as direct driven. In battery coupled PV pumping systems, the electricity produced charges a battery. During low – light conditions, cloudy days or at night, this battery can be used to power the water pump. The overall pumping time is prolonged due to the charged batteries. But attaching a battery to the PV system will also increase the cost. The batteries will control the operating voltage instead of the

PV cells and that will lead to overall decreased efficiency [4]. For direct driven PV pumping systems, the electricity generated is used to run the water pump. As a result, there is no back – up power and no water can be pumped when there is no sunlight. An important factor affecting the amount of electricity generated in such systems is the angle as well as the intensity of the solar radiation during the day. Thus, the amount of electricity produced and water pumped varies throughout the day. However, the advantages of direct driven PV pumping systems are simple design, no battery requirement and thereby are less expensive [4].

### **B. Motor based PV pumping systems**

Motor based PV pumping systems can be broadly classified into two categories based on the types of pumps used: (i) induction motor (AC motor) water pumping systems, and (ii) DC motor water pumping systems. Induction motors are preferred over DC motors as the latter have maintenance issues and are expensive [10,11]. The DC system consists of a PV array, a motor and a pump. It may or may not have an intermediate converter attached to the system. Induction motor based pumping systems cannot be directly connected to the source PV array. Induction motors are AC motors; therefore an inverter system needs to be attached with the converter to convert the output voltage to variable AC voltage. The inverter used is chosen based on its advantages and its output is fed to the induction motor. The choice of converter-inverter system fed to induction motor is critical for effective operation of induction motor. Converters like Buck, Boost, and Buck-Boost are popularly used for photovoltaic systems. As these converters are limited to work at low power, therefore they cannot carry out PV applications for pumping, which are carried out at high power. Thus a new push pull converter, which is a two switch topology can do justice by providing a high power throughout.

1) Types of Induction motor (AC motor) pumping system: Induction motor (AC motor) pumping systems can be further classified into single and multi – stage pumping systems. The multi – stage water pumping systems consist of PV array, DC – DC converter, DC – AC inverter, an induction motor and the water pump. As the AC pumping motor cannot be directly attached to the PV cells, the DC – DC converter with the peak power tracking algorithm is used which is connected to the AC – DC inverter to convert the DC voltage to variable voltage [12]. A single stage AC water pumping system comprises of an AC – DC inverter with a tracking algorithm to convert the DC voltage to variable voltage or variable frequency current for the induction motor. This induction motor is mechanically attached to the water pump. To increase the speed of the pump, the motor speed needs to be increased, which can be achieved by increasing the frequency of the inverter [12]. Table 1 and 2 summarizes the performances of induction motor based solar water pumping systems and other types of solar pumping systems.

**TABLE I. SUMMARY OF IM BASED PV WATER PUMPING SYSTEMS**

| <b>Summary</b>                                                                                                                                                           | <b>Conclusions</b>                                                                                                                                              | <b>source</b>           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
| A comparative study was carried out to investigate whether a DC motor or an induction motor driven centrifugal pump performed better for a solar powered pumping system. | More mechanical power could be derived from the DC motor. However, induction motor was more reliable, had less maintenance issues and was more cost –effective. | Zaki and Eskander, 1996 |

|                                                                                                                                                                             |                                                                                                                   |                                                                      |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|
| A PV water pumping system replaced a conventional power supply for a village and a workshop.                                                                                | The new system was able to successfully meet the 20 m <sup>3</sup> /day demand.                                   | Yahya and Sambo, 1995                                                |
| Loss models for PV pumping systems were tested for the following combinations<br>DC motor with MPPT<br>DC motor without MPPT<br>AC motor with MPPT<br>AC motor without MPPT | DC motor based system was more efficient than the PWM based induction motor system.                               | Lujara et al., 1999                                                  |
| A solar water pumping system was installed in a desert well in Jordan.                                                                                                      | The system was successful in computer simulations and experimental conditions.                                    | Daud and Mahmoud, 2005                                               |
| A DSP based variable system was tested in an induction based PV water pumping system in a rural area.                                                                       | The solution had a single PCU with a three – inverter output but with an extremely complicated MPPT algorithm.    | Ozdemir et al., 2014                                                 |
| An inexpensive, low voltage and single –step PV system was tested out. The system used an                                                                                   | The system turned out to be economically feasible, more efficient, required low input voltage, was a single –step | Jain et al., 2015                                                    |
| OEWM with the pump.                                                                                                                                                         | PV and robust. However, OEWMs are not commercially available.                                                     |                                                                      |
| A PV pumping system was optimized using a single stage solution for a three cascade inverter.                                                                               | The system run near MPP, using a three – level cascade inverter is more efficient than two level – inverter.      | Chinthamalla et al., 2016                                            |
| A smart Solar Water Pumping System with Bidirectional Power Flow Capabilities .                                                                                             | In this paper, a concept of smart solar water pumping system.                                                     | Indian Institute of Technology Delhi, New Delhi-110016, India , 2016 |
| Grid Interactive Bidirectional Solar PV Array Fed Water Pumping system                                                                                                      | Single-phase solar pumping system enhances power quality and source sharing.                                      | Indian Institute of Technology, Delhi New Delhi , 2016               |
| Intelligent grid interfaced solar water pumping system                                                                                                                      | Intelligent solar pumping system ensures efficient, sensorless control and grid support.                          | Utkarsh, bhim ,shaikndra , 2016                                      |
| Three Phase Grid Interfaced Solar Water Pumping System                                                                                                                      | Three-phase solar pumping system uses Vienna rectifier for                                                        | Utkarsh, bhim ,chinmay , 2017                                        |

|                                                                                                       |                                                                                                                                                                   |                                                                                                                                  |
|-------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                       | efficient, reliable operation.                                                                                                                                    |                                                                                                                                  |
| Vienna Converter Fed Two Stage Grid Connected Photovoltaic Pumping System                             | Vienna converter-based solar system ensures efficient pumping and improved power quality.                                                                         | Utkarsh, bhim ,chinmay , 2017                                                                                                    |
| A PV-Grid Fed DTC Based Induction Motor Drive for Water Pumping                                       | Bidirectional PV-grid system enables efficient pump control and grid power export.                                                                                | Saurabh , Bhim , 2018                                                                                                            |
| Development of grid-connected solar water pumping system utilizing bridge                             | Grid-connected SWPS ensures efficient SPV use, stable control, and high reliability.                                                                              | Mahmad asraf A.Mulla ,2020                                                                                                       |
| Grid interfaced solar water pumping system with improved space vector modulated direct torque control | Smart water pumping system offers efficient SPV-grid sharing with reduced complexity.                                                                             | Priyanka Singh, Prerna Gaur 2020                                                                                                 |
| Improved Control Strategy for Water Pumping System Fed by Intermittent Renewable Source               | Storageless pumping system replaces batteries with water storage, enabling cost-effective renewable energy use through adaptive FOC control and modular design.   | Amine BenRhouma <sup>1,2</sup> ,Xavier Roboam <sup>3,*</sup> , Jamel Belhadj <sup>1,2</sup> and Bruno Sareni <sup>3</sup> , 2020 |
| Green energy solution for grid integrated solar PV system for water storage towers                    | Power management in solar PV-grid water pumping system ensures efficient, stable performance with multi-objective control and compliance with IEEE 519 standards. | Rashmi Rai <sup>*</sup> , Bhim Singh , 2024                                                                                      |

### ***C. Factors affecting the PV water pumping system***

According to the usage, the pumps used in PV systems can be classified as surface mounted pump set or deep well pump set [4]. Surface mounted pumps are used when it is needed to pump water through a pipeline, in which and these pumps are required to be located close to the surface of the water. Some disadvantages of this type of pumps are: exposure to extreme weather conditions, limited suction abilities, increased mechanical failures, high maintenance cost and low efficiency because of power losses. Surface mounted pumps tend to suffer from cavitation as well. However, these pump sets are very versatile in nature and that makes it ideal for agricultural purposes. The deep well pumps on the other hand will not function unless it is completely submerged in water. This type of pump propels water to the surface unlike the surface mounted pumps. Deep well pumps do not have to survive the harsh environmental conditions [4].

There are other parameters which affect the functioning of a solar PV water pumping system. The parameters include environmental conditions, type of the PV being used and the arrangement of the PV array to name a few.

1) Environmental factors: Some of the environmental parameters that affect the PV panel are solar irradiation, meteorological conditions, air mass and indirect radiation.

2) Solar irradiation: Solar irradiation (expressed in  $W/m^2$ ) is the amount of solar power which is incident on the surface per unit area. Irradiation has crucial role in deciding the number of PV panels to be used in the system [13]. The USA and Europe are leading in PV technology but African countries receive higher solar irradiation. With increased irradiation, the electricity production also increases.

3) Meteorological conditions: Clearness index defined as the ratio of global irradiance to the extra-terrestrial irradiance emitted by the sun [14]. This clearness and the temperature dictate the irradiance on this planet. The clearness index and the air mass affect the solar irradiance intensity, and its distribution. When there is increase in clearness index and decrease in the air mass, the average energy of a photon will also rise [14]. The temperature of an area rises with increase in irradiance. Therefore, in the absence of irradiation data, the temperature information can be used to design the PV panels [14].

#### ***IV. PV PANELS***

PV cells structures consist of semiconductors in two layers containing the p-n junction for the electric field formation. DC power is generated by these cells due to the opposite movement of electron and hole pairs [13]. PV cells usually produce low voltage, and hence, need to be connected in series to produce larger voltage output.

##### ***A. Materials used in PV***

Broadly there are two types of PV cells when classified on the basis of materials used: (i) crystalline, and (ii) thin film. Crystalline PV cells have better efficiency than thin film PV cells. However, some thin film cells work very well, like cadmium – telluride (Cd-Te) and are not very expensive either [14]. Gallium – arsenide (Ga-As) has the highest efficiency, but it also is one of the most expensive. Mono and poly- crystalline silicone PV cells have become popular due to their economic feasibility. Their performance is better than the thin film cells as well. Among mono and poly – crystalline cells, mono crystalline cells have higher efficiency although the manufacturing cost of both types is same. Thus, it will be advisable to use mono – crystalline PV cells in the pumping systems. A new type of fire resistant PV cells integrated with roofing tiles was put forward. These cells are supposed to be cheaper and easier to manufacture, and have better design and applicability.

Soitec[16] and CEA-Leti, France and the Fraunhofer Institute of Solar Energy Systems (ISE), Germany, developed a multi – junction solar cell which has a conversion efficiency of 46% (Soitec,2014). These multi-junction cells are applied in concentrator photovoltaic systems (CPV) to produce cheaper electricity in areas with large solar radiation. In 2015 a cadmium telluride (Cd-Te) cell achieved an efficiency of 22.1 % [17].

##### ***B. Azimuth and tilt angle***

Angle between the PV array and the surface of earth is known as tilt angle. Azimuth is the angle between the position of sun at a specific time and the true north. PV panels are optimized by running simulations in accordance to the conditions of the area and the tilt angle is fixed. Some PV panels come equipped with a sunlight tracker which adjusts its position according the sun to utilize maximum solar energy. Azimuth and tilt angle play a major role in extracting the highest efficiency from solar panels. One study in Taiwan shows that the tilt angle has more contribution towards the efficiency of the PV cells than

azimuth [14]. However, sunlight tracking in the PV systems will increase the cost and will require high maintenance.

### **C. PV cell characteristics**

The voltage and current are shown to rise with increasing irradiance [18]. But as the temperature of the PV panel increases, the voltage decrease and there is a slight increase in the current. Park and Yu [19] states that with increase in cell temperature, the overall performance of the PV system decreases (equations 1 – 5).

## **V. INDUCTION MOTOR BASED PV WATER PUMPING SYSTEM**

Zaki and Eskander [20] investigated two pumping systems to extract the maximum mechanical energy. To drive a centrifugal pump load, one pumping system used a separately excited DC motor while the other used an induction motor. It was concluded that the maximum derivable mechanical power depends on the type of motor used and the torque – speed characteristics of the load in the system. The separately excited DC motor system achieved maximum mechanical power by controlling the excitation of the motor and connecting directly to the PV cells. The induction motor, on the other hand, must be connected to the PV array via an AC – DC inverter. The frequency of this voltage inverter can be controlled to ensure maximum mechanical power to operate the system in a stable range. Comparison of the mechanical power derived from both the system revealed that the separately excited DC motor was better at utilizing the power generated from the PV array because DC motor can be directly connected to the PV array which also makes it cheaper. However, the induction motor is more reliable and has less maintenance issues. For bigger PV systems, a smaller size of induction system works just as well, thus, reducing the cost differences.

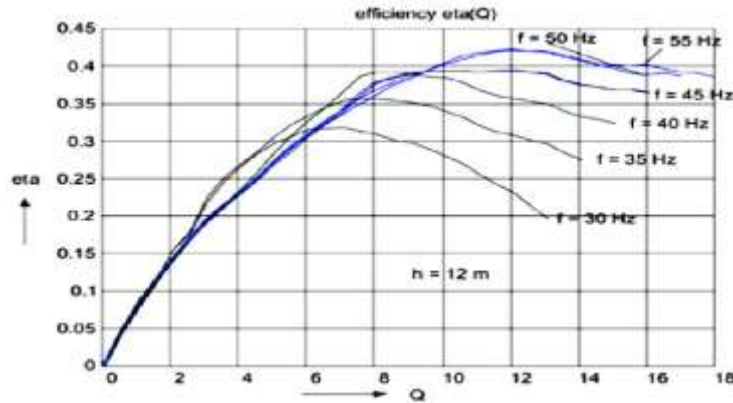
In Nigeria, the conventional power supply for Usmanu Danfodiyo University's mechanical workshop and a neighbouring village was replaced by a PV water pumping system of 1500 watt [21]. The system had a constant – voltage three – phase inverter, a 1.5 HP induction motor and a switch box. The area in question received an average radiation of 5kWh/m<sup>2</sup>/day. The new pumping system was successfully able to meet the 20 m<sup>3</sup>/day demand.

Lujara et al., [22], presented loss models for two PV systems with and without using MPPT. Further two types of motors, namely DC and AC motors, were used for the comparative study. The DC motor system comprised of a PV array, a DC – DC converter, to be used for MPP tracking, a permanent magnet DC motor (PMDM) and a progressive cavity pump. The induction motor system comprised of the same parts. However, instead of a DC motor, an induction motor was used. A PWM inverter was needed to be connected to convert the DC voltage to variable voltage. It was concluded that the DC motor system with MPPT controller was more efficient than the PWM inverter based induction motor system.

A PV water pumping system was installed in a desert well in Jordan [23]. The system used an induction motor which could supply an average amount of 50 m<sup>3</sup> with a head of 37 m daily. There was a total of 5.5 kW/m<sup>3</sup>/day radiation in that area. The system consisted of a PV array, an inverter, an induction motor and a pump. A mathematical model was prepared for computer simulation and then experimental measurements were also carried out. The mathematical model was found to be well suited and the experimental results matched with the simulation results [23]. The paper suggested that the pump be operated at the flow rate and head corresponding to the maximum efficiency as claimed by the manufacturer of that pump. The dependability of the PV system for long term use was verified both by computer simulations as well as by experiments conducted in the

natural environment. Fig. 3 shows the variation of efficiency with changing flow – rate at a constant pumping head of 12 m.

**Fig. 3. Efficiency variation with flow rate of water pumping system.**



The development and testing of a DSP (digital signal processing) based variable drive for a PV system with an induction motor is also used for generation of mechanical energy for ventilation purposes in rural areas[24]. The solution proposed has a single PCU with a three –inverter output which makes it efficient; but the MPPT used was extremely complicated. To find a cheap, low voltage and single –stage step PV water pumping solution with a broad operating bandwidth, Jain et al. [25] proposed a system with a PV array, dual inverters, controller with MPPT and DSAZE PWM algorithm and a three –phase open –end winding induction motor (OEWM) with pump. OEWM uses two –level voltage source inverters to get a three –level inversion which is a major advantage [26]. This system was designed to be economical by using a single –stage system; as the V/f control is integrated with MPPT, the DC bus voltage is less; a three level inverter gives better performance; low input DC bus voltage also increases the PV operating bandwidth and the system is capable of operating in various environmental conditions. Jain et al. [27] developed another single –stage PV pumping system with an OEWM, which functioned with a control algorithm which is a combination of MPPT, sample averaged zero –sequential elimination (SAZE) PWM and V/f control. This system consisted of 2 two –level inverters whose outputs are attached to the OEWM, which in turn is connected to the pump. These inverters run SAZE PWM, which will control the input phase –voltage of the OEWM. To combat switching losses, the algorithm clamps the output of one inverter while switching on the other. Simulations of this system were tested for harsh environmental conditions, which were later verified by experimental runs conducted on a prototype. Both these systems have the advantages of being more economic, simple control strategy and more durable over the system developed by Ozdemir et al. [28]. However, OEWMs are not available for commercial use and till it becomes available in the market, a solution with a low cost, single –stage three –level PV pumping system with a simple motor and MPPT control is required [29].

Chinthamalla et al., [29] proposed a PV water pumping system by optimizing a single –stage solution for a three cascade inverter. The mathematical model is shown in Fig. 5, and equation 6-8. The PV source model was developed using basic unit model of a PV cell. The electrical equivalent current–voltage characteristic for the PV array using basic cell equation is given by:

$$6) \quad i_{pv} = N_p \left\{ i_{sc} - i_s \left[ e^{\frac{q(V_{pv})}{N_s \eta K T}} - 1 \right] \right\}$$

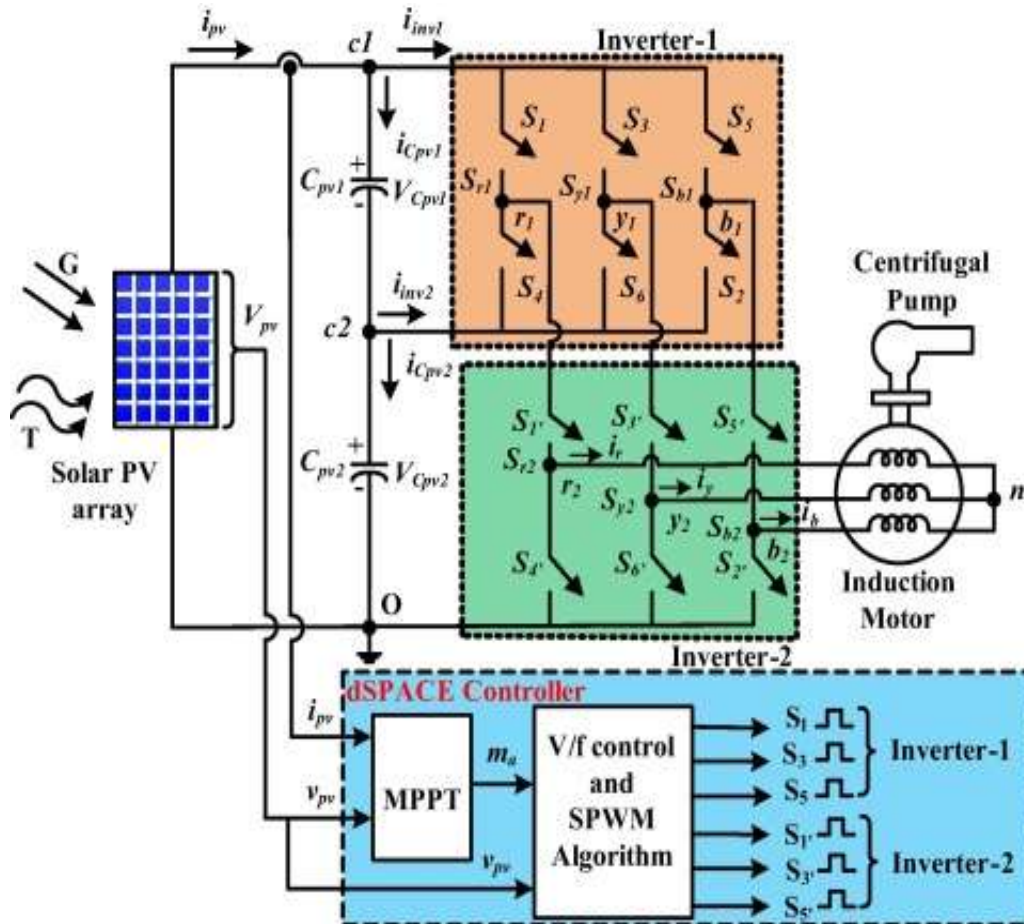
where,  $i_{pv}$ ,  $i_{sc}$ ,  $i_s$  are the PV array current (A), the short circuit current of PV cell (A), and the reverse saturation current of diode (A) respectively. The short-circuit current depends on the Sun insolation (G) and the temperature (T).  $N_p$  and  $N_s$  are the number of parallel and series connected PV cells respectively,  $i_s$  is the diode ideality factor,  $k$  is the boltzmann constant,  $q$  is the electron charge,  $T$  is the array operating temperature in kelvin and  $v_{pv}$  is the PV array voltage (V). In simulation, the PV array voltage ( $v_{pv}$ ), insolation (Suns) and the temperature ( $^{\circ}\text{C}$ ) are taken as inputs for the calculation of PV array current as given in Eq. (3) [29]. The output terminals of PV array are connected to three-level cascaded inverter via buffer capacitors  $C_{pv1}$  and  $C_{pv2}$  (Fig. 5) applying KCL at terminal nodes 'c1' & 'c2' of buffer capacitors [29],

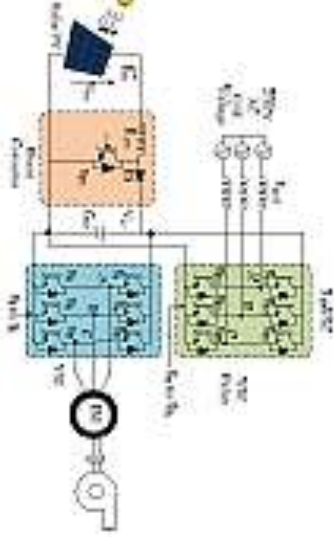
$$7) \quad i_{pv} = i_{C_{pv1}} + i_{inv1} = C_{pv1} \frac{dv_{C_{pv1}}}{dt} + i_{inv1}$$

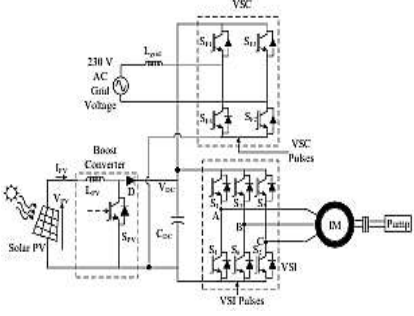
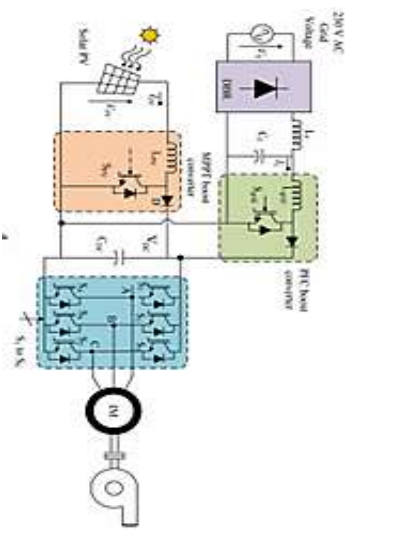
$$8) \quad i_{C_{pv1}} = i_{C_{pv2}} + i_{inv2} = C_{pv2} \frac{dv_{C_{pv2}}}{dt} + i_{inv2}$$

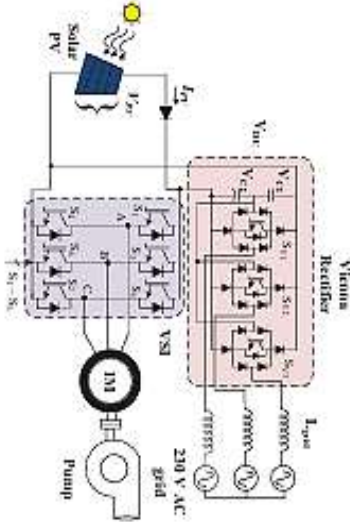
where,  $G$  is sun insolation,  $T$  is the array operating temperature,  $i_{pv}$  is PV array current,  $i_{inv}$  is the current drawn from inverters,  $v_{pv}$  PV array voltage,  $C_{pv1}$  and  $C_{pv2}$  were buffer capacitors,  $v_{C_{pv}}$  is the voltage across the capacitor and  $i_{C_{pv}}$  is the current across the capacitor. The system consisted of a PV array, a three level cascade inverter, a three – phase star connected squirrel cage induction motor, a centrifugal pump and a dSPACE controller (Fig. 6). They concluded that a PV system with an induction motor using a three – level cascade inverter performs better than a system using a two – level inverter. The performance of this system can be justified as the PV system could be operated near MPP.

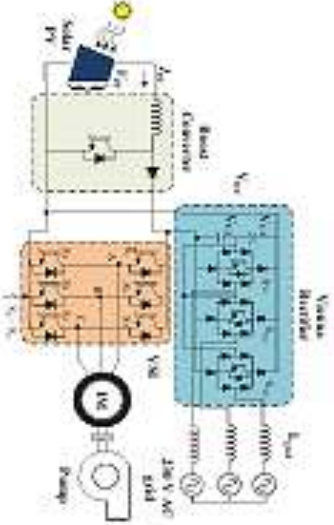
**Fig.4. dSPACE controller model of solar powered water pumping system.**

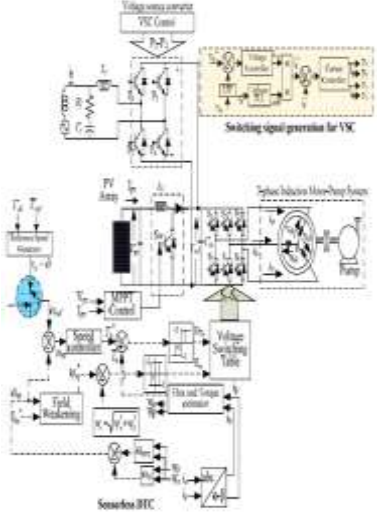


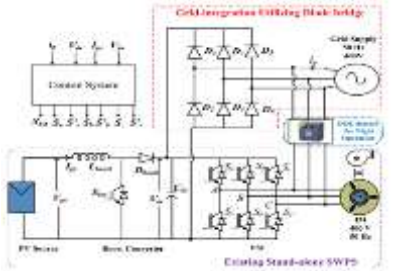
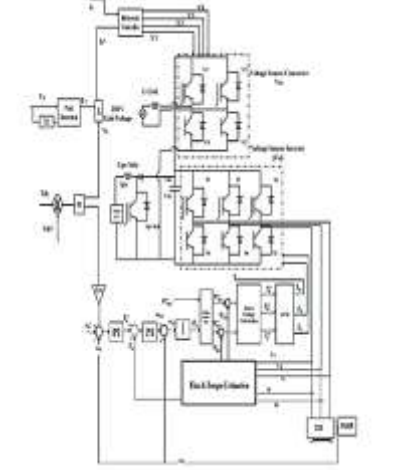
| Abstract                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Conclusion                                                           | Figure                                                                             |
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| <p>This paper presents a smart solar water pumping system with the grid interactive features using an induction motor drive. To alleviate the burden on the electrical grid, solar PVs (SPV) can be used to power up the agricultural and irrigational loads. The system is designed not only to provide the rated discharge of water but also to feed the surplus power to the grid. The SPV array is operated at the maximum power (MPP) point ensuring its efficient utilization by monitoring the power output of the SPV array. Four different modes of operation of the system are identified and a universal control for all the modes is proposed. The uninterrupted operation of the pump is ensured even in the absence of the grid. A variable frequency inverter (VSI) operates the induction motor. Moreover, a voltage source converter (VSC) is used for the bidirectional flow of power in the proposed system. The system is modeled in the MATLAB/Simulink and the simulated results demonstrate the effectiveness of the proposed system in integrating the SPV source into the grid</p> | <p>In this paper, a concept of smart solar water pumping system.</p> |  |

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| <p>—This paper proposes a grid interactive bidirectional solar water pumping system using a three phase induction motor drive (IMD). A single phase voltage source converter (VSC) is used to direct the flow of power from grid supply to the pump and back to the grid from SPV array. A boost converter is used for the maximum power point tracking (MPPT) of the SPV array. A smart power sharing control is proposed, with preference given to the power from SPV array over the grid power. Moreover, the grid input power quality is also improved. Various modes of operation of the pump are elaborated and the performance of the system at starting, in steady state and dynamic conditions are simulated. The simulated results show the novelty and the satisfactory performance of the system.</p> | <p>Single-phase solar pumping system enhances power quality and source sharing.</p>             |    |
| <p>This study proposes a solar photovoltaic (SPV) water pumping system integrated with the single phase distribution system by utilising induction motor drive (IMD) with an intelligent power sharing concept. In addition to the power exchange from SPV to the IMD, a DC-DC boost converter is utilised as a power factor correction unit and a grid interfacing device. For good utilisation of SPV</p>                                                                                                                                                                                                                                                                                                                                                                                                       | <p>Intelligent solar pumping system ensures efficient, sensorless control and grid support.</p> |  |

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| <p>array, it is necessary to extract maximum power from the SPV array. To meet this objective, an incremental conductance based maximum power point tracking control is implemented. Whereas, to control the IMD tied to voltage source inverter, a simple voltage/frequency control technique is used. The proposed topology is designed and tested in the laboratory under standalone, grid interfaced and in mixed mode under various operating conditions.</p>                                                                                                                                                                                                                                                               |                                                                                                  |                                                                                     |
| <p>—This paper presents a new topology for a three phase grid interfaced solar water pumping system. An induction motor driven pump is fed from the solar PV array and a three phase grid using a Vienna converter. The novelty of the proposed system lies in the operation of the pump at rated water discharge when it is operated with the support of the grid. The Vienna converter serves the purpose of power flow from the grid. Moreover, it also improves the power quality at the AC mains. The proposed system is well suited for the areas where the grid support is available. The induction motor is controlled using the open loop scalar (volts/Hertz) control on account of its simple implementation with</p> | <p>Three-phase solar pumping system uses Vienna rectifier for efficient, reliable operation.</p> |  |

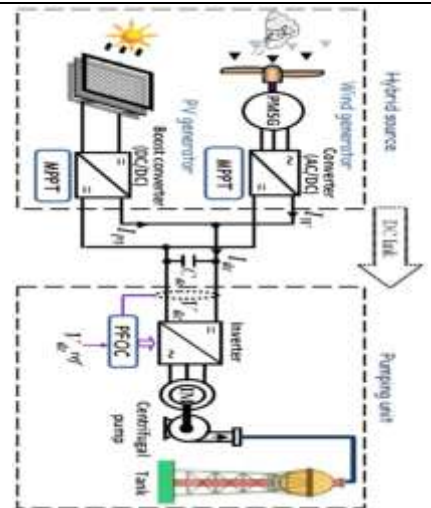
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| <p>reduced sensors. Based on the availability of the power source, the modes of operation are identified and performance of the system at starting, in steady state and dynamic conditions are simulated. Simulated results show the satisfactory performance of the proposed system.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                  |                                                                                     |
| <p>A topology of Vienna converter fed two stage solar water pumping system interfaced with three phase grid supply is proposed. The system uses a Vienna converter, a boost converter and a voltage source inverter to drive an induction motor (IM) coupled centrifugal pump. The proposed system helps in eliminating the loss of water discharge due to varying solar insolation in standalone solar water pumping systems. The IM is controlled using simple scalar control while the maximum power point tracking is achieved using the incremental conductance technique. The input power quality is improved by the constant frequency switching of the Vienna converter. Various modes of operation on the availability of active power sources are identified and the photovoltaic pumping system (PVP) is modelled and its performance is simulated in detail. The</p> | <p>Vienna converter-based solar system ensures efficient pumping and improved power quality.</p> |  |

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| <p>system indices at starting, steady state and with varying solar insolation levels are analyzed. The simulated results show the feasibility of the proposed system in grid connected locations.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                           |                                                                                     |
| <p>This paper presents an effective technique for uninterrupted water pumping irrespective of insolation level. Moreover, the system is capable of adjusting the power flow as per the requirement. A sensorless direct torque control of induction motor is used to drive water pump. One VSC (Voltage Source Converter) is used for utility grid interface and one VSI (Voltage Source Inverter) is used for the induction motor control. The PV array is connected to the DC link with a power converter for providing constant DC-link voltage. The UVT (Unit Vector Template) theory is utilized to control the bidirectional power flow between the three-phase VSI and DC link voltage connecting an induction motor drive coupled water pump on the other end. The suitability of the system is shown through various power transfer modes of operation and are validated on prototype developed in the laboratory.</p> | <p>Bidirectional PV-grid system enables efficient pump control and grid power export.</p> |  |

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| <p>CPG, constant power generation; DOL, direct on-line; FSM, finite state machine; IM, induction motor; MPPT, maximum power point tracking; PFC, power factor correction; SPV, solar photovoltaic; SVPWM, space vector pulse width modulation; SWPS, solar water pumping system; VSC, voltage source converter; VSI, voltage source inverter.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                             | <p>Grid-connected SWPS ensures efficient SPV use, stable control, and high reliability.</p>  |   |
| <p>In this paper, 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 that have smart sharing of power between grid and solar photovoltaic array is proposed. A boost converter with variable step size MPPT that automatically tracks the next step size to maximize the power output is used. Four distinct types of modes with grid operative system and SPV array are proposed such that the unceasing performance of pump is guaranteed and surfeit power is fed back to the grid. The proposed system is modeled in Matlab/Simulink, and the plausibility and novelty of the system in amalgamating the SPV source into the grid can be verified by the results.</p> | <p>Smart water pumping system offers efficient SPV-grid sharing with reduced complexity.</p> |  |

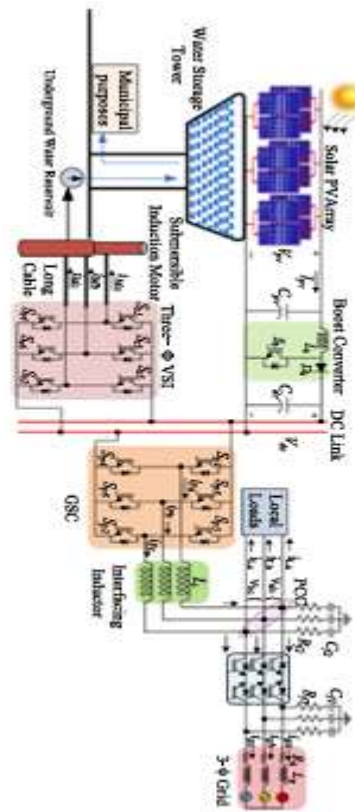
This paper focuses on a water pumping system fed by a hybrid (PV-Wind) generator. The water pumping system uses centrifugal pumps driven by variable speed Induction Motors (IM) controlled by a Field Oriented Control (FOC). The absence of battery storage to decouple sources and power demand is the main originality of the contribution, together with the typical adaptation of the FOC strategy. Furthermore, the absence of battery storage will consequently lead to fixing the system operating point at a steady state which is imposed both by the intermittent renewable energy sources and by the hydraulic load characteristics. The basic idea is then to adapt the system impedance by using the two degrees of freedom offered by the power source inverter in order to control, firstly, the DC bus voltage and, secondly, the rotor flux of the induction machine; the adaptation of the FOC strategy is based on this idea. Simulation results clearly confirmed by experimental investigations show the satisfying performance of the system even with variable powers of the intermittent renewable source.

Storageless pumping system replaces batteries with water storage, enabling cost-effective renewable energy use through adaptive FOC control and modular design.



In India, water storage towers are present almost everywhere, especially across small towns to rural areas. The storage tanks either utilize diesel powered or utility grid fed induction motor (IM) water pumps. The large spaces available with water storage towers can be utilized to plant solar PV panel for large storage towers water pumping operation, hence, making a switch from diesel or grid run storage towers to solar operated storage towers. This paper presents a robust control of grid integrated solar PV-based water pump system with efficient and smooth transition between standalone and grid interfaced modes. A smart DC link voltage control is presented for distributed generation system (DGS), which provides full control on DC link voltage for both modes of operation at all dynamic load conditions. An enhanced phase-locked loop (EPLL) control is utilized for grid source converter (GSC) in grid control operation, making it flexible to different grid scenarios and power quality. It works for harmonics suppression, load balancing and grid side converter control. An enhanced phase-locked loop (EPLL) is implemented for synchronization control

Power management in solar PV-grid water pumping system ensures efficient, stable performance with multi-objective control and compliance with IEEE 519 standards.



|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  |  |
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| <p>algorithm, which provides an accurate estimation of voltage angle even during frequency ramps and exhibiting superior performance particularly in terms of robustness against DC offsets. The primary requirement for smooth operation of grid-tied solar PV system is effective power management between different sources. The issues of power management and power quality, are discussed in this work, and solutions are presented. The implemented control algorithms are tested successfully for dynamic solar insolation, varying load conditions, unbalance in load, sudden grid outage condition. The system appropriateness is validated by experimental results.</p> |  |  |
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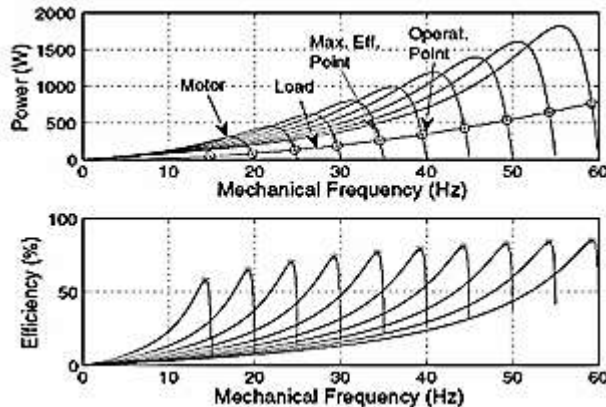
#### **A. Induction motor control**

Induction motors are an important contributor in electricity consumption and industrial growth. In an induction motor, control can be established in two ways, stator and rotor sides. For stator side control, the stator poles are to be regulated, supply voltage will need to be controlled and a rheostat will need to be attached to the circuit [30]. For rotor side control, adding external resistance on the rotor side or injection of a slip frequency emf should be enough [31]. A SPWM inverter can be used to control the motor speed. The frequency and amplitude of the sinusoidal signal can be modified to get the required motor speed. Pulse Width Modulation (PWM) is another control algorithm which can be used by fixing an input voltage and controlling the output AC voltage to effectively control the motor speed [32]. It is essentially a closed loop control system as the inverter output voltage is controlled by a feedback mechanism installed in the inverter. Three – phase induction motors are an essential part of the electrical industry. But over the past few decades the use of multi – phase induction motors have increased. Multi – phase motors can smoothen the torque pulse, reduction in rotor harmonic losses, reduction in the harmonic content and overall dependable for the system. Bojoi et al. [33] proposed the use of a simple digital PWM technique for harmonic minimization of multi – phase induction motor. Welchko et al. [34] concluded that to make methods fault tolerant, monetary investment is required. Induction motors usually fail due to stator faults.

Condition monitoring technology for the induction motors is equipped in online detection of faults in the motor [35].

Field-oriented control strategies are employed to make high-performance induction motor control. Motor control in photovoltaic pumping must be focused on delivering maximum power and motor efficiency. Power delivery can be maximized by controlling the torque, while optimization of efficiency of motor can be done by managing the motor magnetic flux level. Fig. 5 shows that at low electrical frequency the induction motor has low efficiency [32], as practically the motor runs with no load at low speed. The motor operating point can be shifted towards maximum efficiency by altering the magnetic flux level.

**Fig. 5. Efficiency variation with electrical and mechanical load.**



Other ways of making Induction motor control are: through indirect field-oriented control (IFOC) scheme, and by the direct torque control (DTC) technique. Induction motors are devised such that they show high efficiency at rated load, voltage, and frequency. Induction motors can run on application of varying speed and load, which is required for some applications where voltage or frequency or both needs to be varied. In these cases, by choosing a suitable level of magnetic flux for the motor high-efficiency operation is possible. Vitorino et al. [32] selected the most suitable magnetic flux level by evaluating three different methods. The methods were based on power factor adjustment, empirical search for a minimum-loss operating point, and balanced d and q currents. Control strategy directly affects the use of either rotor or stator magnetic flux for improvement in motor efficiency is a direct consequence of the.

#### III. CONCLUSION

Extensive work has been done in the field of solar PV since the 1970s. Besides the components, parameters like the PV material and environmental conditions also affect the efficiency of solar water pumping system. Induction motor water pumping system is becoming popular as it is less expensive, requires low maintenance, and is reliable, small in design and efficient. The main objective in developing the PV water pumping system is to minimize the cost per unit power produced. The single – stage water pumping system is worth considering as it promises to be a simple system with very effective results. Other upcoming technologies like PV – CSP hybrid systems will need further development to utilize its combined advantages of two technologies. Increasing efficiency, cost effective technologies and cheaper manufacturing process will give a great boost to this technology as a versatile and dependable PV water pumping system.

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