Design and Development of a Solar PV Inverter for Water Pumping Applications

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***Abstract*— Proper management of irrigation is one of the major challenges faced by the agriculture sector in India. In a country where agriculture is practiced mostly in the interior parts, the availability of grid is very much irregular thus restricting mechanization and adoption of new technologies in this sector. Power generation from conventional resources cause pollution and their exhaustion is bound to occur very soon. In this context, utilization of the naturally available solar power for operating irrigation pumps could be a plausible solution to the farmers in the rural areas. This paper describes the design and development of a solar photovoltaic (PV) inverter which is used to drive a water pump for irrigation purposes. The inverter output is fed to a three phase ac induction motor which drives the pump. The inverter can be operated in two modes – the former, using MPPT (Maximum power Point Tracking) technique, wherein the dc-dc converter is controlled in such a way that the solar PV panel is always operated at the maximum power point and the latter wherein the flow rate of the pump is controlled by varying the speed of the motor by means of an inverter. Design aspects of the inverter and the control strategy involved are also presented in this paper.**

Keywords—PV Array, Water Pumps, MPPT, V/f control, Solar PV Inverter

I. INTRODUCTION

Agriculture provides employment opportunities to nearly two-thirds of the Indian population and contributes significantly to the national income. India ranks second worldwide in farm output and earns foreign exchange. Even though agriculture plays a significant role in the India's socio-economic development its contribution to the GDP is drooping [1]. Slow agricultural growth is a thought of concern because most of our population is dependent on rural employment for a living. The agricultural practices that are currently followed are neither economically nor environmentally sustainable and hence the yields of many agricultural commodities produced in India are low. Poorly maintained irrigation systems and lack of good infrastructure for implementing modern technologies in farming are some of the important factors responsible for this scenario.

Irrigation in India can be broadly classified into two types-surface irrigation and ground irrigation. In case of surface irrigation, there is no effective management for the volume of water stored, the volume used for irrigation or on what volume can be added to this water. Therefore the farm output and hence the economy relies solely on the Monsoon season. Ground water extraction involves utilization of underground water which causes environmental problems when the user consumes water disproportionately. This creates problems for the other users and affects the water table as well.

Improving the irrigation systems that are currently prevalent can improve the production and bring about a significant growth in our economy. Water pumps used for irrigation need either electricity or diesel. The non-availability of electricity and the cost of fossil fuels make the farmers reluctant in implementing proper irrigation techniques. Utilization of solar energy to run water pumps could be a blessing in disguise to the rural population who are engaged in agriculture.

Solar water pumps are driven by either dc motors or ac motors. The dc voltage generated by the solar PV arrays are inverted, filtered and fed to an induction motor [2]. The block diagram of a solar water pump is as shown below.

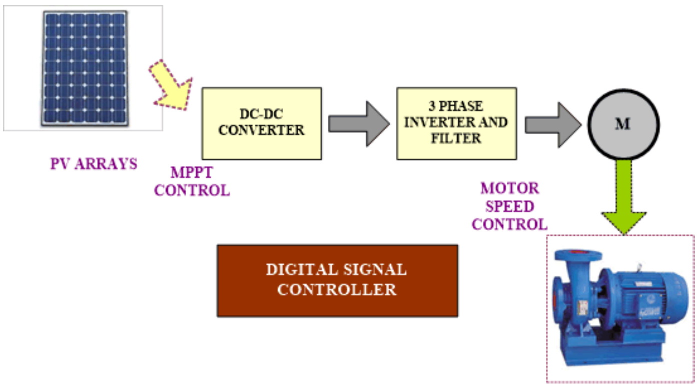

Fig 1. Block Diagram of a 3 phase Solar Water Pump

For dc motors the dc voltage from the solar panels are used to control the motors which in turn adjusts the flow rate of the pump[3,4]. In case of ac motors, the dc voltage is converted into ac voltage by means of an inverter and then the filtered output is used to run a single phase or a three phase motor.

II. LITERATURE SURVEY

A. Variable frequency drives

Over the years significant advances have been made in the area of variable frequency drives used for speed control applications. The control system can be installed remotely at a suitable location. Static frequency inverters provide soft start as compared to the online starters thus reducing the maintenance costs. Inverters convert a constant amplitude voltage (dc) into a variable frequency-variable amplitude voltage (ac). Varying the frequency supplied to the motor produces the variation of the speed of the rotating field which varies the mechanical speed of the machine [5]. For a constant torque load then varying the amplitude and frequency of the voltage supplied to the motor with their ratio being a constant results in constant flux and hence constant torque as long as the current remains unchanged. So the motor is capable of providing continuous adjustments of speed and torque to a mechanical load. By keeping the slip constant at any speed for a given load, the losses can be minimized for various load conditions. Flow-restricting valves or moveable air vanes are frequently used to control flow rate for the applications where flow requirements vary. But this may cause frequent maintenance issues for the mechanical equipment involved. Variable-frequency drives enable pumps to operate under fluctuating demand and consuming less energy at the same time meeting the pumping needs.

B. V/f control of an ac electric motor

Single-speed drives start motors sharply, subjecting the motor to high torque and producing current surges up to 10 times the full-load current. In contrast, variable-frequency drives enable "soft start", gradually ramping up a motor to the operating speed. This reduces the mechanical and electrical stress on the motor thus bringing down the maintenance and repair costs and improves the motor life.

A variable frequency drive can result in significant energy savings. For centrifugal pumps even a small reduction in motor speed will highly leverage the energy savings. A variable frequency drive controlling a pump motor makes it run at a speed less than full speed and this can substantially reduce energy consumption as compared to a motor running at constant speed for the same time duration. The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

C. PV Array Sizing for pumping applications

The PV array is described by its current-voltage characteristic function as:

$$I_{PV} = n_p I_{ph} - I_{rs}[\exp(\frac{q(V_{PV} + I_{PV} R_{RS})}{AKTn_S}) - 1) - \frac{V_{PV}}{R_{Sh}} \quad (1)$$

where I_{PV} and V_{PV} are the PV array's current and voltage, respectively, I_{ph} is the cell's photocurrent, R_{sh} and R_s are the intrinsic shunt and series resistances of the cell. n_s and n_p are the number of cells connected in series and the in parallel, q=1.602·10^{-19} C is the electron charge, K=1.3806·10^{-23} J/K is Boltzman's constant, A=2 is the p-n junction ideality factor, T is the cell temperature (K), I_{ph} is the cell photocurrent (it depends on the solar irradiation and temperature), $I_{ph} = I_{sc} * \frac{G}{1000}$, and I_{rs} is the reverse saturation current of the cell (which depends on temperature), G is the solar irradiance (W/m^2) and V_{PV} is the cell voltage[4].

According to the specifications given by the Ministry of New and Renewable Energy (MNRE) under the Jawaharlal Nehru National Solar Mission programme, the Solar PV Water Pumps with PV array capacity in the range of 200 Watt to 5 kWp could be installed on a suitable bore-well, open well, Water Reservoir, Water stream, etc considering the average daily solar radiation condition to be 7.15 kWh/ sq.m. on the surface of PV array.

The minimum water output from a Solar PV Water Pumping System at different total dynamic heads can be calculated. The SPV water pumping systems may use surface mounted motor pump-set, submersible motor pump set or a floating motor pump set. The PV array size recommended for a 2HP AC motor pump set and an inverter is 1800Wp for shallow (surface) solar pumping applications for a dynamic head of 15m[6].

The size, and subsequently the cost, of a photovoltaic system depend upon two factors: the electrical requirements of the devices (loads) relying on the system and the amount of sunshine available to power the system. Both factors determine the quantity and size of panels, batteries, and other components.

- **Daily Load**

  The amount of electric power being consumed at any given moment is called as the 'load'. The wattage of a device is generally printed on the device nameplate. The load estimate must be very much accurate to calculate the sizing of any system. Oversizing the system during design may result in wastage of money whereas under sizing may cause power shortages or malfunctioning of the system. Hence proper considerations must be taken while calculating the PV array sizing in this case[7].

  The design to calculate the PV sizing starts with the calculation of the daily load given by

  Daily load = Wattage x Time in use (2)

  The nature of the load, along with the amount of sunshine received at the place considered, can be used to calculate the size of the array.

- **Available Sunshine**

  The amount of sunshine is specified in peak hours which means the hours of the day during which the maximum rated performance from a solar panel is expected. This depends on the location at which the panels are mounted. Panels are rated in peak watts, the amount of electricity that is produced during peak sunshine. Thus, the number of watt-hours which can be obtained from a panel is determined by

Panel Watt-hrs = Number hours of peak sunshine x panel output (as per the rating) (3)

- **Sizing of the Array**

As batteries and inverters consume a certain amount of the power generated by the solar cells, it is suggested to allow for at least a 20 percent safety margin over and above the exact calculated load needs.

Number of panels = Daily load x 1.2 Watt-hours (4)

D. *Centrifugal Pumps*

A pump forms the heart of most of the irrigation systems. To make an efficient irrigation system, the pump selected depends upon the requirements of the water source, the piping system and the irrigation equipment.

Pumps generally employed for irrigation applications include centrifugal, submersible, deep well turbine and propeller pumps. Centrifugal pump pertains to any pump located above the water surface and using a suction pipe [7-10].

Before selecting an irrigation pump, a detailed study of the conditions under which the pump will operate must be done. This includes

1. The source (well, river, pond, etc.)
2. The pumping flow rate required
3. The total suction head
4. The total dynamic head

The source of the water could be either surface water or well water and its availability will be determined by the geological conditions. However, the flow rate and total dynamic head depends upon the type of irrigation system, the distance from the water source and the design of the piping system.

The centrifugal pump is the most popularly used pump in the world. The working principle is simple and the pump is robust, effective and relatively inexpensive. Single-stage centrifugal pumps are frequently used in PV shallow water pumping for low head applications whereas for PV subterranean water pumping and surface water pumping with higher heads, multistage centrifugal pumps are more suitable. Other pump types such as progressive cavity pumps and piston pumps have also been utilized [7].

The centrifugal pump creates an increase in pressure by transferring mechanical energy from the motor to the fluid through the rotating impeller. The fluid flows from the inlet to the impeller center and out along its blades. The centrifugal force hereby increases the fluid velocity and consequently the kinetic energy is transformed into pressure [8]. The selection of the pump depends on the water consumption profile and the hydraulic head, any pump is characterized by its absorptive power, which is obviously a mechanical power on the shaft coupled to the pump [7, 8].

$$P = \frac{\rho g H Q}{\eta} \tag{5}$$

The power consumed of the absorptive power and the developed pump torque are respectively [9,10]

$$P_u = \rho g H Q \tag{6}$$

$$T_L = a_0 + a_1 \omega + a_2 \omega^2 \tag{7}$$

III. Design and Hardware Set up

The hardware set up of the proposed system consists of a three phase inverter for 2kW comprising of six IGBT switches (three limbs) designed to drive a 2.2kW, HP 3 phase induction motor. The general topology of a three legged inverter with the motor – pump set is as shown in Fig 2.

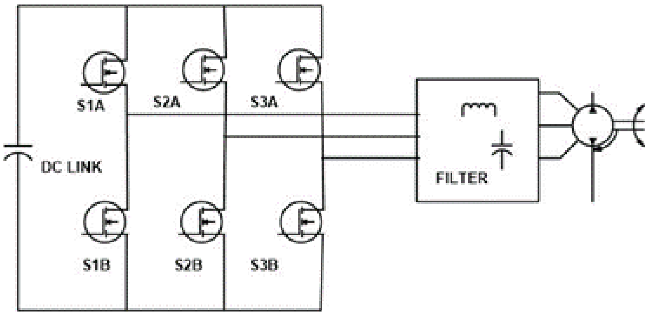

Fig 2. Schematic of a 3 phase inverter driving a motor-pumpset

The control of switches is established using sine PWM method in order to generate the switching pulses.

Modes of operation

The inverter can be operated in two ways.

- Operating the solar PV panel at the maximum power point. In a ‘direct-coupled’ system, a PV array is directly connected to a load, The operating point of the system will be at the intersection of the I–V curve of the PV array and load line [4]. Maximum power point trackers (MPPTs) maximize the power output from a PV system for a given set of conditions, and thus maximizing the array efficiency. For this the dc side voltage and using hill climbing algorithm, the maximum power point is tracked. The DSP ensures that the solar PV is operated at the maximum efficiency irrespective of the weather conditions.
- In the second mode, the inverter operates with the dc link voltage available from the PV. This power would fluctuate on hourly basis or sometimes even less than that. But, in any case, the inverter should be operated in closed loop in order to run the induction motor. The speed control of the induction motor is established through V/f control, so as to deliver the required flow rate.

Fig 3 shows the hardware setup of the solar PV inverter. The dc link voltage is maintained by four capacitors which can be connected in series or two switches in series followed by parallel combination according to the dc link voltage specifications. The dc link voltage varies throughout the day as it is directly connected to the PV arrays. The output voltage of the inverter would also vary according to the dc voltage. There are four driver ICs out of which three are used to turn on the top three switches and the fourth one to turn on the bottom switches as they are all referenced to the common ground. The isolated power supplies needed for the drivers are also designed and implemented. The output of the three phase inverter is to be fed to a 3Φ induction motor whose speed is controlled by V/f control and this controls the flow rate of the pump.

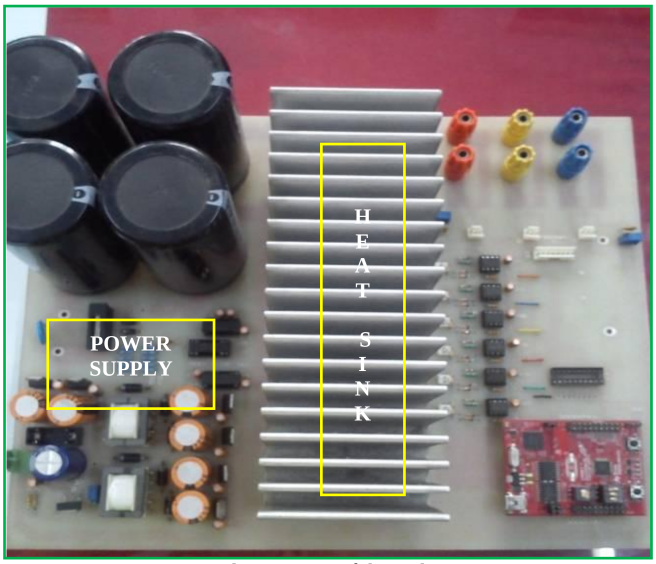

Fig 3. Hardware set up of the 3 phase inverter

The inverter can be split up into the following sections

DC link Section

The DC link side comprises of four capacitors which can be connected in series or parallel combination of two branches each consisting of two switches in series. These capacitors are capable of holding the dc voltage generated by the solar PV arrays. Changing the series and parallel combinations gives an additional feature of increasing or decreasing the dc link voltage from the solar panels. An MOV is also connected in parallel to the dc link to protect the inverter. The voltage sensing circuit which is used to sense the dc link voltage is implemented using an optocoupler IC ISO122 from Texas Instruments along with a voltage divider network.

Power Supply Section

The power supply section consists of two flyback converter switchers manufactured by Coilcraft LM2587. The switchers provide two 12V and one 5V isolated supplies for the drivers LM 3185and the buffer IC 74HC244NA. The outputs of the switchers are regulated by the positive and negative 3 terminal regulators LM7812, LM7805 and serve as the power supplies for the drivers and the buffer.

Inverter Section

The inverter section is made up of six IGBT switches G4PH50UD along with the RC snubbers. The driver section which consists of 4 drivers give the control voltages which turn on or turn off the switches. The top three switches have isolated voltage supplies while the lower switches are triggered by a single driver IC. The main function of the gate drive circuit is to transform the logic level control signals into the appropriate voltage and current for efficient, reliable, switching of the IGBT module.

The driver stage devices and series gate resistance R_G must be selected to provide the appropriate peak current for charging and discharging the IGBT gate. Another function of the gate drive circuits is to provide isolation so that the logic signals are not connected to the dangerous high voltages which are present in the power circuit. The driver must also be immune to the severe electromagnetic noise produced by the fast switching, high voltage, and high current IGBT power circuit. Careful layout and component selection is critical to avoid problems of noise getting coupled to the circuit.

Filters and the Current Sensing Circuits

The current sensors used in the inverter are ACS714 Hall Effect based linear current sensors as shown in Fig 4. The current sensors are SMD ICs which are soldered on the bottom side of the PCB.

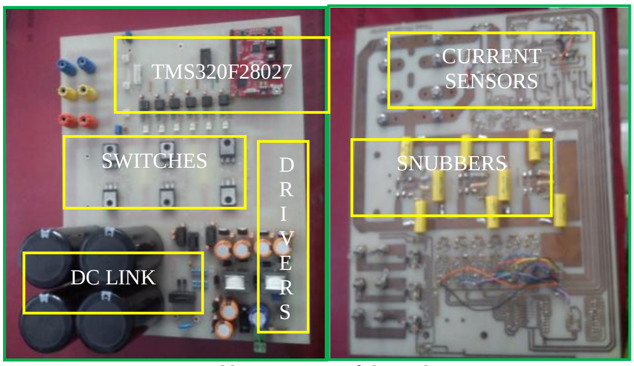

Fig 4. Top and bottom view of the 3 phase inverter

IV. CONTROL STRATEGY OF THE INVERTER

The inverter and the filter generates 3 phase sinusoidal voltage which drives the 3 phase induction motor. A centrifugal pump is used for pumping water. The flow rate is controlled by the speed of the induction motor. The induction motor speed control is established by V/f control (Fig 5).

The dc-dc converter is made to operate under maximum power point tracking technique, thus increasing the efficiency of the system. The I_{dc} and V_{dc} on the dc link side is sensed to operate the solar PV arrays at the maximum power point. Hill climbing method, perturb and observe method and incremental conductance methods are some of the algorithms used for MPPT. When the PV output varies, the power supplied at the input side also varies. In this system, hill-climbing method is used to track the MPP [9-11].

The VSI is operated in the voltage controlled mode to make the operation closed loop. The output voltage of the inverter is sensed and converted to the d-q reference frame, thus generating Vq and Vd values. An internally generated sine template is used for implementing the phase locked loop required for the transformation. The compensators (PI controllers) compare the reference values with the Vq and Vd values and appropriately tune the error value zero. Again, the dq to abc conversion generates the template that is used for SPWM generation. The analog to digital conversion, frame transformation, compensation and the SPWM generation is implemented in software by DSC TMS320F28027.

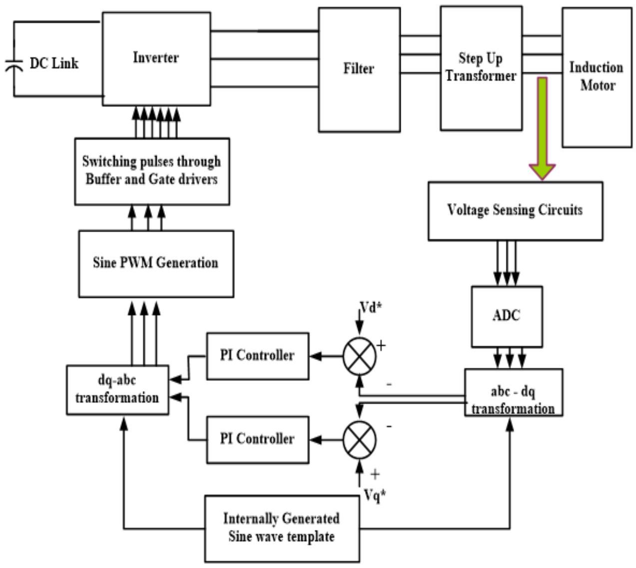

Fig 5. Control strategy of the 3 phase inverter

V. SIMULATION AND HARDWARE RESULTS

The whole system was simulated in MATLAB simulink and the simulation results are explained below. The output voltage from the 3 phase inverter after filtering are shown in Fig 6.

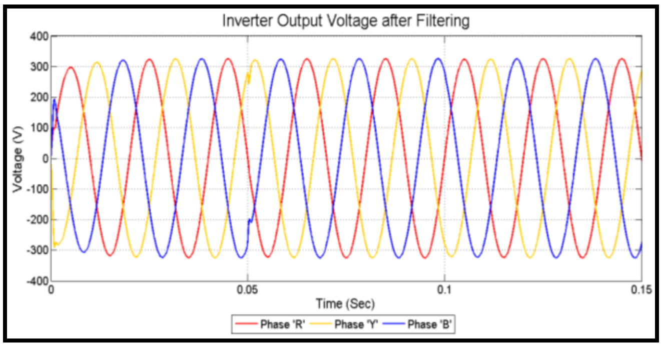

Fig 6. Filtered 3 phase output voltage of the inverter

The mathematical model of control scheme is programmed in C-programming language and implemented through the digital signal controller TMS320F28027. The CCSv4 platform provides the facility of reading from and writing data to DSP while the program burned on DSP is running. The CCSv4 also enables plotting sensed or processed variables graphically. Few of the hardware results obtained on DSO as well as some graphs plotted on CCSv4 software are presented below.

The gate driving pulses are generated using DSP-TMS320F28027 with SPWM technique. The switching frequency of PWM pulses is selected to be 20 kHz. Fig 7 shows the PWM pulses generated for driving one leg of inverter. The nature of PWM pulses is complementary and appropriately designed dead band is provided to avoid shoot-through.These pulses are then buffered and fed to the drivers to turn the switches on and off.

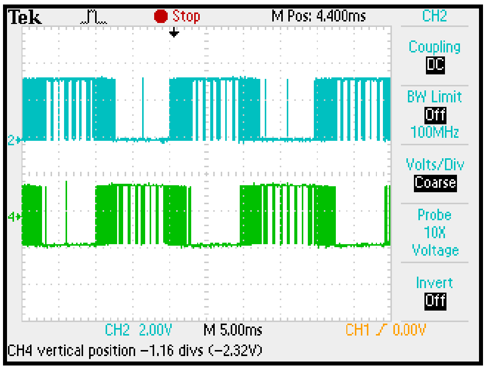

Fig 7. Complementary PWM pulses driving a single leg of inverter

The phase to phase output voltages of the inverter before filtering are as shown in Fig 8. When the inverter output voltage is passed through a low pass filter, sinusoidal voltage is obtained. The inverter three phase output voltages after filtering are shown in Fig 8.

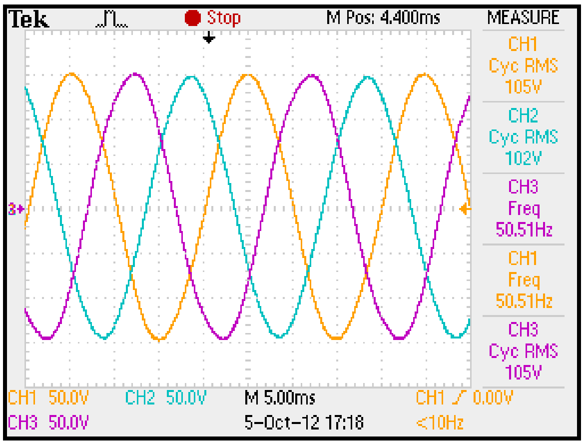

Fig 8. Output voltage of the Inverter

The sine and cosine templates required for a-b-c to d-q and d-q to a-b-c transformation matrix are generated internally using DSP-TMS320F28027. The output voltage of the 3 phase inverter plotted on the CCS platform was captured and is presented in Fig 9. The values of the various currents and voltages can be observed in the watch window and can be changed in real time. The graph tool in CCS platform provides an opportunity to view the waveform on real time basis.

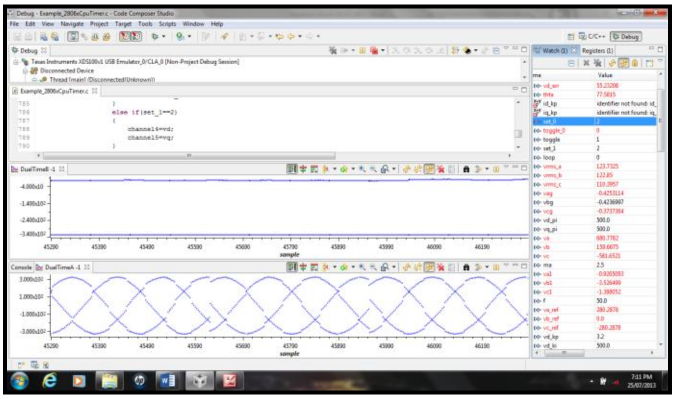

Fig 9. Three phase sensed voltage after software filtering

VI. CONCLUSION

India is a country of high solar insolation with the daily average solar energy incident over India varying from 4 to 7 kWh/m^2 and approximately 1,500–2,500 sunshine hours per year. Utilization of this abundantly available clean solar power for pumping applications can prove to be a blessing for the rural population whose sole income is from agriculture. Using solar based water pumps can bring about a positive growth in the farm output especially in the interior parts of the country where grid availability is discontinuous. A solar water pump comprises of solar PV arrays, dc-dc converter with MPPT , a three phase inverter-filter driving an induction motor which in turn runs the pump. It helps in saving energy, is easy to operate very much reliable and also reduces the dependence on rains.

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