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Design and Implementation of SPV Array Fed Water Pumping System Using BLDC Motor under Partial Shading Condition

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ABSTRACT: This paper is based on Solar Power fed Water Pumping System. One of the most intriguing applications for distributed energy generation is photovoltaic pumping. Despite this, as compared to other energy sources, cost remains a concern. As a result, improving efficiency can be viewed as one method of cost reduction. Using a maximum power point tracker allows for more energy to be generated with the same number of panels, resulting in more energy per panel. Nonetheless, there are more than panels in the entire power processing system. Converters, inverters, electrical motors, pumps, and batteries are also included, which store energy for later use during a solar outage. .A DC-DC conversion step is frequently required in solar PV fed water pumping that is driven by a brushless DC (BLDC) motor in order to maximise the solar photovoltaic (PV) generated power using a maximum power point tracking (MPPT) technique. This power conversion stage adds to the cost, size, complexity, and inefficiency of the system. This study is a one-of-a-kind solution that involves a single-stage solar PV energy conversion system feeding a BLDC motor-pump, eliminating the need for a DC-DC conversion stage. For BLDC motor control, a simple control system capable of operating the solar PV array at peak power utilising a common voltage source inverter (VSI) is proposed.The suggested control does away with the phase current sensors on BLDC motors. There is no supplemental control linked with the motor-pump speed control and gentle start. The speed is controlled by the solar PV array's maximum power. The applicability of the proposed system is demonstrated by its performance evaluation using MATLAB/Simulink-based simulated results and experimental validation on a prototype constructed under real-world settings.

Keywords-MPPT, Solar PV array, BLDC motor, Water pump, VSI, Soft starting, Speed control.

I. INTRODUCTION

Because of the rise in population, industrialisation, and transportation, energy consumption is on the rise. With this growth in energy consumption, fossil fuel depletion is at an all-time high. Around the world, people are making genuine attempts to harness renewable energy sources and utilise them for their social and economic development. Solar energy is recognised as the most viable source of energy among all existing renewable energy sources. Solar energy is considered the most viable source of energy among all available renewable energy sources, and its efficient harvesting can easily meet the world's current energy demand. Solar-photovoltaic-based systems have emerged as a feasible alternative for irrigation, residential uses, space planes, and industrial use in India, which has abundant sunlight but limited fossil-fuel resources. Solar energy is remarkably exclusive form of renewable energy sources which has procurement increasing attention in modernistic year. Solar power generation is always clean and pollution-free, as well as a bend in nature. As a result, solar power is commonly used in places where it provides the most benefits from the source. The cost of a solar PV panel has decreased in recent years, increasing interest in solar PV applications in today's world. PV energy conversion is now seen as one of the most promising alternatives to fossil fuel-based electricity generation systems, as it produces no harmful pollutants, emits no greenhouse gases, requires no maintenance, and uses no water.However, the technology is still in its early stages, and there are a number of issues to be solved, including intermittency, high initial costs, and low efficiency. Applications based on renewable energy sources are utilised in industries and in the household. Water pumping is the most effective, critical, and cost-effective application for solar PV array power generation of all other applications.Water resources play an important role in world's economy. They are not only essential for satisfying human needs, protecting health, food

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production, and the restoration of ecosystems but also for economic and social development. There is a great and urgent need to supply sound technology for the provision of drinking water. Pumping systems for water are an important part of addressing this need. Solar water pumping systems are gaining popularity in the agricultural and industrial sectors since they are environmentally benign and do not require the use of fossil fuels.

Water pumps that run on electricity are unreliable, and diesel pumps have higher fuel costs. Conventional water pumps run by electricity tend to be unreliable and diesel pumps have increased fuel cost. The solar irrigation pump system is the system in which solar energy is responsible for the operation of the pump. Energy obtained from the sun is called solar energy and this is renewable source of energy and is in huge amount. Monitoring the water level of the soil along with manual operation of the irrigation pump is a tedious job. Therefore, the proposed system employs solar energy for the same by using photovoltaic cells rather than electricity which is commercially available.

Induction motors and dc motors are utilised for water pumping systems in rural and grid-connected areas, respectively. Pumping load is usually done with a basic, low-cost, and efficient motor. Generally, induction motors are preferred for pumping applications because they are inexpensive and perform well under any load condition. However, when induction motors are used for solar PV applications, they suffer from overheating and require complicated control because the voltage of the motor drops too low. In low-voltage situations, an efficient, dependable, and cost-effective motor is required. As a result, the BLDC motor is used in such applications.Brushless DC motors are an excellent choice for applications requiring great reliability, efficiency, and power-to-volume ratio. In general, a BLDC motor is designed to be a high-performance motor capable of producing massive quantities of torque across a wide speed range. For pumping applications based on solar PV, BLDC motors are unquestionably competing with any other motor since they provide greater performance as well as soft starting.

BLDC motors are a step up from conventional DC motors, and they have nearly identical torque and speed curves.Brushes are the main difference between the two. The combination of a BLDC motor for pumping system technology and a solar PV source boosts the system's usage and reliability. Figure 2 shows a block diagram of a BLDC motor-driven water pumping system.

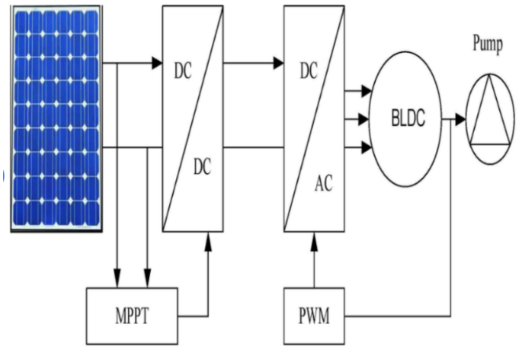

Fig.1. Block diagram of BLDC water pumping system

system The maximum power point tracking (MPPT) technique is used to get the most out of solar PV. In general, the P & O incremental conductance algorithm is employed for MPPT tracking. While incremental conductance performs best under quickly changing atmospheric conditions, it performs poorly at low irradiance levels when employing DC– DC converters. This paper explains how to make the best use of solar PV-based applications and how to soft-start BLDC motors. As illustrated in fig. 1, the following proposed system provides benefits of solar PV based application driven by BLDC motor for water pump.There are various ways to control speed of BLDC motor like hysteresis control and other control scheme are used. But following configuration is simple, low cost, noise free and having least component of the system; make configuration is suitable for water pumping system.

A brief description and conclusion on various papers used as reference in this work.Solar Energy is becoming the latest and pollution free source nowadays. Solar energy is becoming more popular by the day. Solar energy's advantages, such as no pollution and low cost, make it a better option for irrigation than a water pump in areas where electricity transmission is either impracticable or uneconomical. The Brushless DC Motor (BLDC) will be operated utilising solar energy, which has a number of advantages. Water pumping is the most appealing application of solar energy when considering the different advantages of solar energy with BLDC motors, such as high efficiency and low cost. The BLDC Motor's speed is controlled without the use of any additional controls.Eliminate the DC-DC conversion stage by employing the DC link, which reduces the circuit's cost, size, and complexity. The BLDC Motor is turned by using the Voltage Source Inverter, which sends a signal to the PIC controller.PIC controller Eliminates phase current sensors [2]. A comparison between different motors used for water pump application. BLDC motor gives better performance, energy saving and also it is cost effective as compared to the present machines and hence is a better alternative for domestic applications, in view of energy conservation is presented in [3].A solar array system with partial shading detection and a model-free global maximum power point tracking (GMPPT) algorithm.

The suggested approach is divided into three sections: searching, tracking, and detecting and avoiding dead points in partially shaded P-V curves, if any exist. When compared to prior methods [1,] this method performs better in terms of tracking speed and average gathered power. Multiple steps and peaks characterise the current–voltage and power–voltage characteristics of large photovoltaic (PV) arrays under partially shadowed situations.This makes it impossible to track the actual maximum power point (MPP) [global peak (GP)]. Furthermore, under these conditions, most present methods are unable to extract maximum power from the PV array. In partially shadowed settings, [5] provides a novel technique for tracking the global power peak. A feedforward control strategy for operating the dc–dc converter is also presented to accelerate the tracking speed, which leverages the reference voltage information from the tracking algorithm to push the operation toward the MPP.When compared to a normal controller, this controller takes about a tenth of the time to track. For a solar photovoltaic (SPV) array fed water pumping system using a permanent magnet brushless DC (BLDC) motor drive, a boost-buck (BB) DC-DC converter is presented. DC-DC boost and buck converters are cascaded to achieve maximum power point tracking (MPPT) and soft starting of the BLDC motor in order to construct a BB converter with appropriate voltage management.The BB converter combines the benefits of both boost and buck converters, and it appears as an intriguing answer to the challenges that both converters cause in SPV applications. The BB converter has good switch utilisation, high efficiency, non-inverting output voltage, and low stress on power components. [7] investigates the starting, dynamic, and steady state performance of the BLDC motor with the proposed BB converter for SPV-based water pumping under varied atmospheric circumstances.

- In compared to an induction motor driven system, the proposed solution as a BLDC motor driven solar water pumping system offers a high efficiency power conversion. Under light loads, the efficiency of an induction motor decreases when excitation losses take over. As a result, when compared to a BLDC motor, which has no excitation loss due to its permanent magnet excitation, it reduces the volume of water delivered in adverse weather.
- A high-efficiency BLDC motor minimises the size of a PV array and, as a result, the cost of installation. In other words, with a BLDC motor, the number of required PV modules is lower than with an induction motor.
- Because the BLDC motor has a high power factor, the capacity of the utilised VSI is lowered. This feature aids in the cost-effectiveness of PV pumping systems.
- In comparison to an induction motor, the BLDC motor has a high DC bus voltage consumption because it is a rectangular current fed motor. This function also lowers the DC bus capacitor's voltage rating and the VSI switching devices' voltage ratings.
- Unlike an induction motor, the speed of a BLDC motor is not limited by power frequency. Therefore, the rated speed of a BLDC motor can be designed higher, which is beneficial to increase the capacity and decreasing the size. This leads to a compact solar PV water pumping system.
- The proposed BLDC motor speed control technique is significantly simpler than the induction motor speed control technique. Unlike the speed control of an induction motor, the suggested control does not require any additional VSI or phase current sensing.Thus, the aforesaid distinguished features of proposed control, make the solar PV based water pumping system further simple, cost-effective and compact.

The system under investigation is first built by selecting a BLDC motor-pump set and a PV array that will allow it to work successfully under all potential weather situations, and then shown using MATLAB simulation and an experimental system. It performs satisfactorily under the appropriate conditions without sacrificing its performance, particularly when it comes to PV array MPP operation.

II. SYSTEM DESIGN AND SPECIFICATION

An appropriate design and specifications of BLDC motorpump and solar PV array play a significant role in the desired operation of a water pump. A 8-pole, 1500 rpm, 1.32 kW BLDC motor is chosen to drive the water pump. The detailed specifications of BLDC motor are shown in Table I. The PV array, DC link capacitor and BLDC motor are selected such that functioning of the system is not deteriorated even by sudden disturbances in the atmospheric conditions.

Parameter	Motor Design
No of poles	8
Stator outer diameter	122mm
Stator inner diameter	80mm
Length of core	50mm
No of slots	12
Stacking factor	96%
Air Gap	0.5mm
Winding type	3 phase star connected
Rotor outer diameter	79.5mm

Table.1. BLDC motor specification.

PV Array	**Rating**
$V_{MPP} = V_{PV}$	224.7V
$P_{MPP} = P_{PV}$	1890 W
$I_{MPP} = I_{PV}$	8.4A
BLDC Motor Rating	1.32kW
V_{dc}	310V
No.of modules in series	7

Table.2. System Parameters

PV Array	**No. of modules in series**
1	3
2	3
3	1
Total	7
PV Array Rating	1.89 kW

Table.3. Design of SPV array

A. Design of SPV array

The SPV array is systematic arrangement of large series and parallel PV panels which consist of a large number of PV cells. The outer atmosphere of earth has a solar irradiance level of 1.373 kW/m2 and it reduces up to 1 kW/m2 after considering all the losses with a condition of clean and at peak time. The SPV array selected for proposed system is 1.89kW power rating considerably more than BLDC power rating by assuming there is always some conduction and switching losses present in the converters. The capacity of each SPV module is of 60W. The specifications of SPV module areas, open circuit module voltage (Voc) of 38.3 V, short circuit module current (Isc) of 8.9 A. The electrical specification of SPV array is indicated in Table 1. The maximum power for PV array is given as,

$$P_{MPP} = (N_s * I_{MPP}) * (N_c * V_{MPP}) = 1.89kW$$

Where, N_s and N_c = number of sequence and corresponding strings of PV module,

I_{MPP} and V_{MPP} = current and voltage of PV module at MPP.

The PV modules connected in sequence string,

$$N_s = \frac{V_{MPP}}{V_m}$$

PV modules current,

$$I_{MPP} = \frac{P_{MPP}}{V_{MPP}} = 8.41A$$

Number of corresponding strings connected,

$$N_c = \frac{I_{MPP}}{I_m} = \frac{8.41}{2.8} = 3\text{modules}$$

B. Design of DC Link capacitor

A small capacitor connected across the PV array serves as the DC link capacitor of VSI. This capacitor carries the ripple current, which is given as,

$$i_c = i_{pv} - i_{dc}$$

The switching frequency is selected in view of the component size, system response, noise disruption and conversion efficiency. These factors are directly affected by the switching frequency. A high switching frequency results in a reduction in the size of DC link capacitor. It also improves the transient response, and avoids the frequency bands in which noise would be disruptive. On the other hand, a high frequency switching of the VSI, causes a low conversion efficiency. The switching loss increases with increasing switching frequency due to the high number or constant energy switching events in a period.

III. CONTROL APPROACH

Control of the solar PV array operating point using an MPPT technique, BLDC motor electronic commutation, switching pulse generation for VSI, and managing the speed of the BLDC motor are the four primary aspects of the proposed system's control.

A. Maximum Power Point Tracking

The major principle of MPPT is to extract the maximum available power from PV moduleMPPT compares the output of the PV module to the battery voltage before determining the best power that the PV module can provide to charge the battery and converting the best voltage to obtain the most current into the battery. MPPT can extract more current and charge the battery when the battery is deeply drained. Maximum Electricity Point Tracking, or MPPT, is an electrical system that controls the operation of photovoltaic (PV) modules so that they can produce all of the power they are capable of.MPPT is not a mechanical tracking system in which the modules are “physically moved” to aim more directly at the sun. MPPT is a totally electronic system that changes the electrical operating point of the modules to allow them to deliver the greatest amount of power available.Additional power harvested from the modules is then made available as increased battery charge current and the PV module by varying the duty ratio so that the impedance of load and source is varied and matched at the peak power point so as to obtain the maximum power. When the isolation and temperature of a photovoltaic system change, the maximum power point tracking (MPPT) technology is typically used to supply the highest possible power to the load.

20 Photovoltaic (PV) generation is becoming more popular as a renewable energy source due to its numerous benefits, including no fuel expenditures, no pollution, low maintenance, and no noise emissions, to name a few.

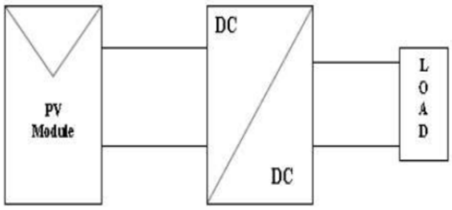

Fig.2. Block diagram of Typical MPPT system.

Controlling maximum power point tracking (MPPT) for the solar array is essential in a PV system. It consists of a DC-DC converter that acts as an interface between the load PV modules still have relatively low conversion efficiency; therefore, controlling maximum power point tracking (MPPT) for the solar array is essential in a PV system. Maximum Power Point Tracking (MPPT) is a technique for extracting maximum energy from photovoltaic (PV) systems that is utilised in power electronic circuits. Many maximum power point Tracking (MPPT) techniques are available and proposed various methods for obtaining maximum power point. But, among the available techniques sufficient comparative study particularly with variable environmental conditions is not done. Over the past decades many methods to find the maximum power point have been developed. These techniques differ in many aspects such as number of sensors required, complexity, cost, range of effectiveness, speed of correct tracking. Among these techniques, the P&O and INC control are the most common. Both P&O and INC control are based on "hill-climbing" principle, which consists of moving the operating point of the PV array in the direction in which power increases. P&O are the most popular MPPT methods due to their ease of implementation, low cost and good performance at varying irradiance condition.

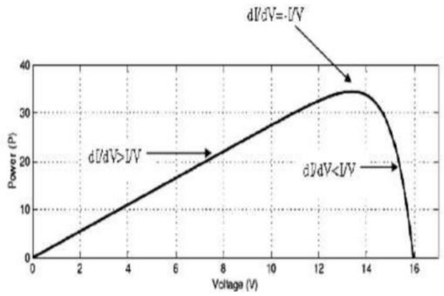

Fig.3. Power versus voltage curve.

Fig.3.shows that the reference voltage or current will increment or decrement continuously based on the previous value and the present value accordingly d_P and d_V is calculated. If $\frac{d_P}{d_V}$ is greater than zero then there is a linear increase of power with respect to voltage. If $\frac{d_P}{d_V}$ is less than zero then there is an increase of voltage with decrease in power. At MPP, change in power with respect to change in voltage is zero.Here, EA-P&O algorithm is to adopted to track the optimum operating point of solar PV array.

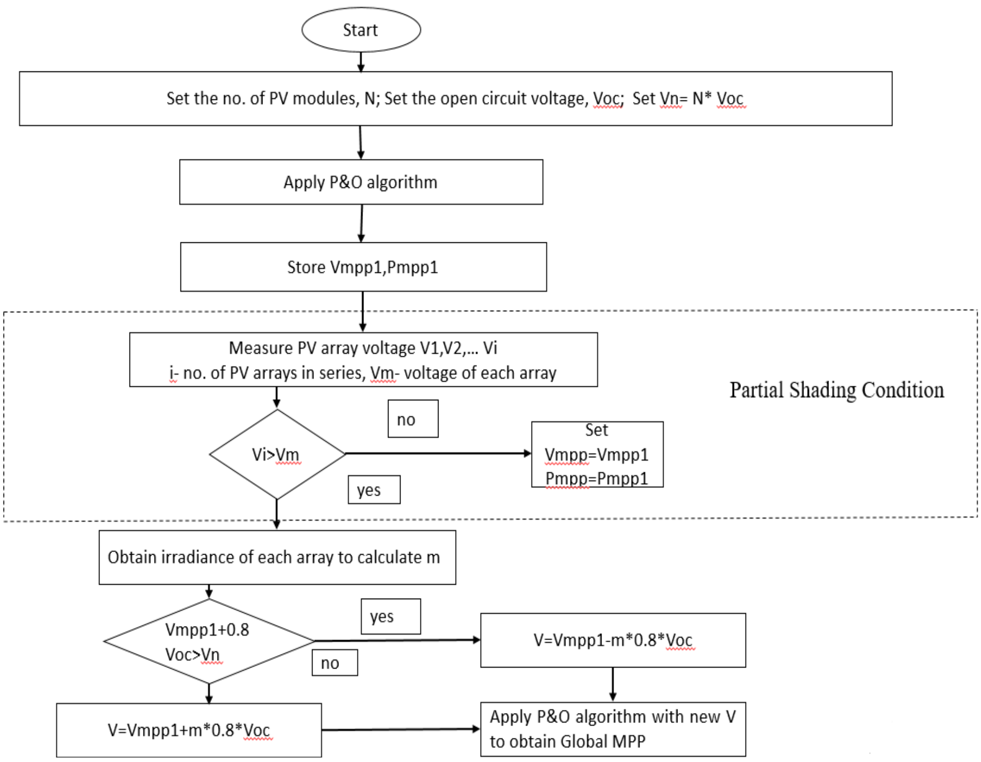

Fig.4. Flowchart of modified EA-P&O algorithm

It has a number of advantages over conventional P&O algorithm is that:

- It minimizes the steady state 0scillation.
- Solves divergence problem by applying dynamic boundary condition.
- The algorithm detects the partial shading occurrences, and perform a rapid search for global peak.
- The value of open circuit voltage and irradiance are continuously updated without use of temperature and irradiance sensors.
- It reduces cost and complexity of MPPT implementation.

B. Electronic Commutation of Brushless DC Motor

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A symmetrical direct current is obtained from the DC bus of VSI for 120° and placed at the centre of back-EMF via electronic commutation (Electro-motive Force).

In accordance with the rotor position, three Hall sensors emit a set of Hall signals (H1-H3) at a 60o interval. These signals are converted into the six fundamental frequency pulses (S1-S6) that determine the VSI switching states using a decoder. At any given time, just two pulses are high, leading in a low conduction loss.

C. Switching Pulse Generation for VSI

The pulses for switching the devices of VSI are generated by linking the output indices of two controls. An optimum duty ratio, D generated by the execution of EA-P&O is compared with a high frequency carrier wave in order to get a high frequency PWM pulse. To modulate the six fundamental frequency pulses (S1- S6) generated through an electronic commutation, an AND logic is used. The AND logic gate receives a high frequency PWM pulse and a fundamental frequency pulse (S1) as inputs and ultimately provides, at the output, a PWM switching pulse (S1) for upper switch of the first leg. Similarly, switching pulses for the remaining switches of VSI are generated using AND gates. A high output (ON) results in only if both inputs to the AND gate are high. As a result, the AND gate simply modifies the ON period of a fundamental frequency pulse with the wave frequency. The suggested water pumping system is thus controlled by combining the EA-P&O algorithm with electronic commutation.

D. Speed Control of Brushless DC Motor

The speed is governed by an available maximum power from the solar PV array. Any variable in the atmospheric conditions, causes a variation in the power output from the PV array and hence in the speed of BLDC motor. In fact, an optimum duty ratio (generated by MPPT algorithm), acting as duty ratio for the VSI, regulates input voltage to the motor by chopping action of VSI. Ultimately the motor input voltage regulates the operating speed. As the duty ratio is varied by the MPPT algorithm, following the atmospheric conditions, the speed of the motor is adjusted accordingly. In addition, fundamental frequency of the six pulses (S1 – S6) varies due to the variation in the switching frequency. This is caused by altering the pulse width S1-S6 using AND logic.

IV. SIMULATED PERFORMANCE

The proposed water pumping system is modelled and its performance is simulated in MATLAB/Simulink.

A. Simulation result of BLDC motor.

Because back-Emf and torque are linked, it is critical to provide an accuratevalue of torque to the model while designing a BLDC Motor drive system. Because the rotor must be rotated, the stator winding must be energised sequentially and commutation must be done electronically, knowledge of the rotor position is required for energising the stator winding in the correct sequence. The variable dc link voltage control technique was used to control the speed, and the results were then confirmed.

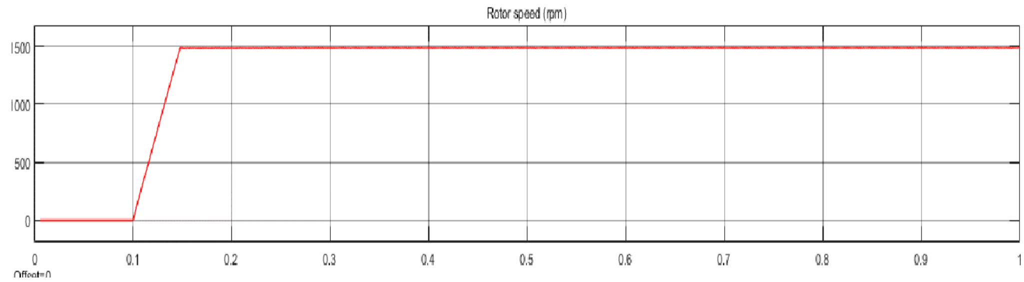

Fig .5. Rotor Speed Vs Time

Fig 6. Torque Vs Time

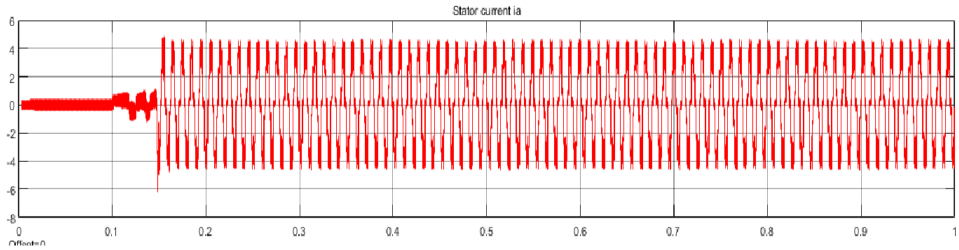

Fig .7. Stator Current

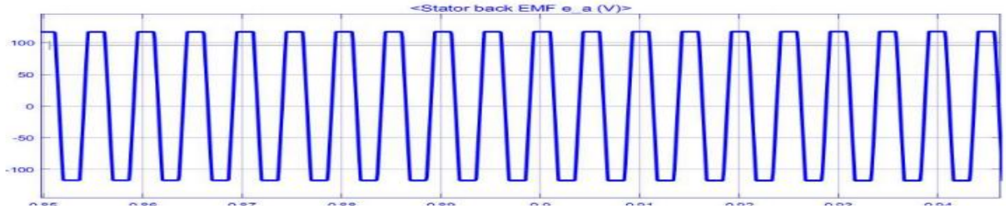

Fig.8. Back emf

B. Simulation result of partial shading arrangement

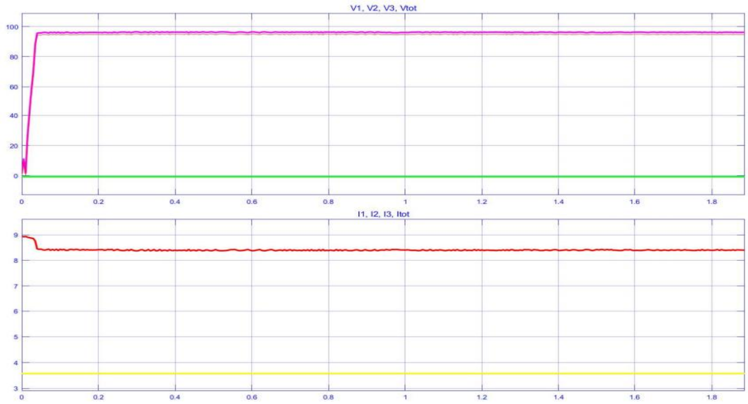

Fig.9. Simulation of the partial shading arrangement

From the simulation result of the partial shading arrangement, red line indicate the current in the panel in which irradiance is high, whereas irradiance is proportional to the current in the PV panel. Whenever, the global MPPT point will work, then only the dc link become constant.

V. EXPERIMENTAL VALIDATION

The developed prototype consists of BLDC motor, PV Panel, Six switch inverter, MOSFET (IR4110), IR2110, dsPIC33FJ32MC202 (Controller). The pump load is realized by a BLDC motor driven DC generator which feeds a resistive load. BLDC motor is an electronically commutated motor with stationary armature and permanent magnet field system on the rotating shaft. Back EMF method is employed for commutating the motor and is powered by DC electricity via an inverter produces an AC current to drive each phase of the motor via a closed loop controller. The implemented motor has ratings as 1hp, 48V, 20A and a rated speed of 1500 rpm. The sensed signals are converted into the digital form through the analogue to digital converters (ADCs) and transmitted to the DSP dSPACE 1104 for execution process. The Hall signals directly transmitted via the digital I/O pins to carry out an electronic commutation and motor control. Finally, the gate pulses are received again through the I/O pins.

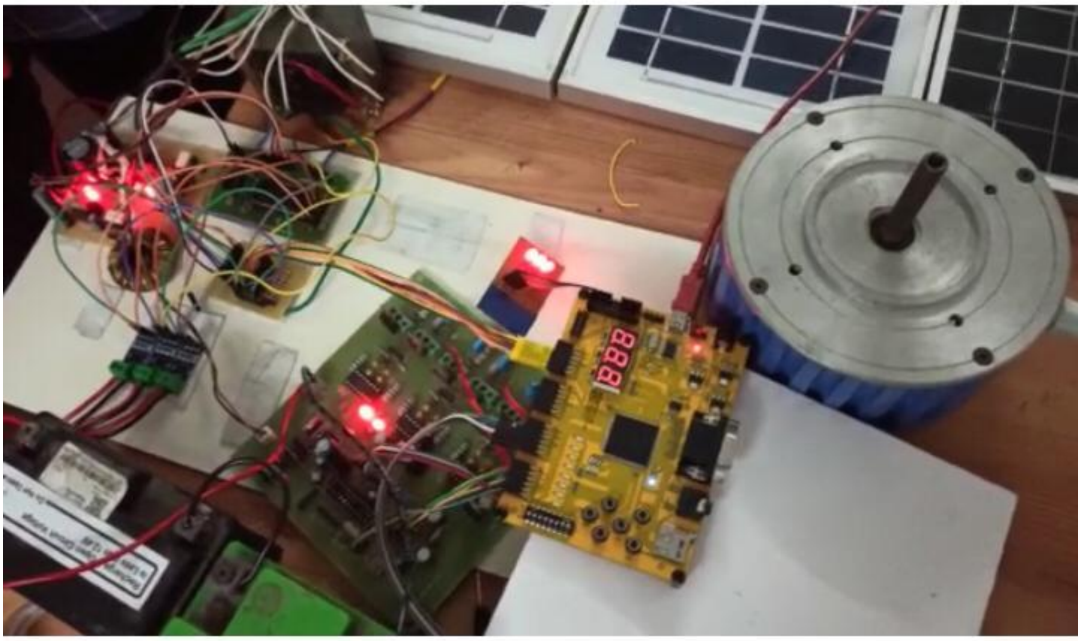

Fig.10. Experimental setup of the submersible BLDC motor drive with partial shading condition.

VI. COMPARISON OF CONVENTIONAL AND PROPOSED SYSTEM

There are several benefits of the proposed system over the conventional schemes. A comprehensive comparison of these systems is tabulated in Table 4. The proposed one appears superior in every aspect. Moreover, efficiency of the conventional and proposed schemes at various irradiance levels, under the identical operating conditions, is estimated based on the experimental measurements. Although the power losses in the water pump are not included in the efficiency calculation. Regardless of the operating conditions, the proposed system seems more efficient than its conventional counterparts.

PARAMETER	CONVENTIONAL SYSTEM	PROPOSED SYSTEM
Voltage (V)	422	484
Current (A)	2.44	3.8
Power (W)	1032	1839
Efficiency	86%	97%
DC bus capacitance	High	Low
BLDC motor control	Complex	Simple
Compactness	Medium	High
Cost	Medium	Low

Table.4. Comparison of proposed and conventional schemes

VII. CONCLUSION

The suggested BLDC motor-driven water pumping system, which is based on single-stage solar PV generating, has been proven. MATLAB toolboxes were used to simulate the system, which was then implemented on an experimental prototype. The suggested system's topology has resulted in a DC-DC converter-free solution for PV-fed brushless DC motor water pumping.In addition, the motor phase current detecting parts have been removed, resulting in a straightforward and cost-effective drive. Other desirable features include speed control without the use of an extra circuit and a motor-pump soft start. The superiority of the proposed work has been demonstrated through a rigorous comparison of the suggested and current topologies.

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