Review of Special Electric Drives aided Photovoltaic Pumping and Proposal of a New Hybrid Grid Interactive Water Pumping System

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Abstract- This paper presents the review of solar photovoltaic PV power fed water pumping system having efficient special electric motor drives. The novelty of the paper is expressed in two perspectives, one proposing an inventive PV grid power export along with brushless DC (BLDC) motor water pumping system and the second novelty lies in the peak power tracking scheme where a direct hunt algorithm is embedded with the well established perturb and observe system. The said work is tested for a 1 kW water pumping system both in simulation and hardware. The results reveal that the photovoltaic power when not utilized for pumping is effectively exported without any complex power electronic interface. Also the proposed direct hunt algorithm is found to be competent even during dynamic variations in irradiation pattern and secures around 95% tracking efficiency.

Keywords- Photovoltaic (PV), renewable energy, maximum power point tracking (MPPT), direct hunt algorithm (DHA), special electric drives.

1. Introduction

Water is the elixir for all living creatures. Regions with no normal stockpile of water need to pump water from underground or from other water sources. Water pumping consumes massive amount of conventional energy sources, which leads to the emission of greenhouse gases, can be reduced by using renewable energy sources[1]. The promising solution for the degrading ecological conditions, increasing demand of energy and depletion of fossil fuels is the power generation using renewable sources. Among various renewable energy sources, solar photovoltaic (PV) is unique due to its major advantages like flexible structure, scalable operation and ever emerging technology[2-3]. Developing countries like India have taken lot of initiatives to encourage PV installations, India has its mission statement of deploying 100 GW of PV by 2025. Solar water pumping application is also an important component in this mission as it is also a potential claim for PV generation[4].

Power Electronic interfaces are mandatory in any renewable energy systems to regulate the source and load power. With respect to the source regulation, the PV power tends to change instantaneously with respect to irradiation and temperature. Therefore, a power-tracking scheme called maximum power point tracking (MPPT) is mandatory to ensure maximum possible power delivery at the given point of time. In photovoltaic fed water pumping system, two topologies are mostly used namely single stage and double stage. In the former type first stage is used for MPP extraction and second stage to regulate the load[5-6].

Table 1. Nomenclature

Abbreviation	Expansion	Abbreviation	Expansion
PV	Photovoltaic	**GI**	Generalized integrator
SPVWPS	Solar photovoltaic water pumping system	**INC**	Incremental Conductance
GCPVS	Grid connected photo voltaic system	**MPPT**	Maximum power point tracking
SEM	Special electrical machines	**P & O**	Perturbation and observe
PMSM	Permanent magnet synchronous motor	**CVT**	Constant voltage tracking
SRM	Switched reluctance motor	**OVT**	Open-circuit voltage tracking
SyRM	Synchronous reluctance motor	**THD**	Total harmonic distortion
PFC	Power factor correction	**BESS**	Battery energy storage system
VSC	Voltage source converter	**CFPS**	Centrifugal pumping system
VSI	Voltage source inverter	**DLFVR**	Double line-frequency voltage ripple

Table 1 presents the nomenclature used in this paper. In single stage the elimination of DC-DC converter makes it more effective as it eliminates the related losses. Although two stage topology has some major advantages like reduced load on VSI and improved control over DC connect voltage at lower solar irradiation[7-8]. During standalone conditions, these both topologies suffer a common problem of discontinuous water pumping as a result of irregular solar irradiation and during night time and bad climatic conditions. Moreover, when pumping is not required, during the abundant supply of solar energy, PV power remains unexploited which leads to the degradation of the efficiency of the connected system.

Due to the varying irradiance level and temperature, P-V and I-V characteristics of the solar photovoltaic system is nonlinear. As a result of this, maximum power extraction is a very difficult issue[9]. To overcome this problem, the best solution is to use the Maximum Power Point tracking technique and the various techniques have been explained in the literature[10]. MPPT's main purpose is to adjust the operating solar voltage near the MPP under changing climatic conditions. It plays a major role and becomes indispensable in all the solar photovoltaic systems[11-12].

At present this induction motor is overcome by the brushless DC motor (BLDC) as it is an energy saving system with some merits like high efficiency, power density and high power factor. Its compactness and increased capacity are the extra features. Initially, these problems have been rectified by using battery energy storage system (BESS) next to the DC link[13]. BESS continues charging and discharging relying on the accessibility of solar insolation and guarantees full water release under all working conditions[14]. However, the drawbacks of battery such as complex system, high upkeep cost and short life span challenged researchers to explore other options. One suitable way for the volatile nature of the weather conditions is to introduce storage tank attached with the pumping system[15]. If sufficient solar irradiation is available, and there is no water need for the farm, storage tank can be filled with the water and this stored water can be used when there is absence of solar input. On the other hand, the integration of storage tank with WPS leads to high system cost and requirement of large space. In order to overcome all these problems, the research works were concentrated towards the integration of standalone solar water pumping system with the grid[16-19]. Installation of grid interactive systems can improve the system efficacy and reduce the complexity. In addition, when there is not enough power from PV array, water-pumping system can be operated with the power delivered by the grid.

PV power will be fed to grid when water pumping is not required by the application. This research work reviews the contribution of researchers in photovoltaic pumping with special electric drives and renders two contributions; one in proposing a new MPPT scheme and another one is introducing an inventive hybrid photovoltaic pumping with grid interactive system.

This article is organized such that section 2 presents the generic photovoltaic pumping system with special electric

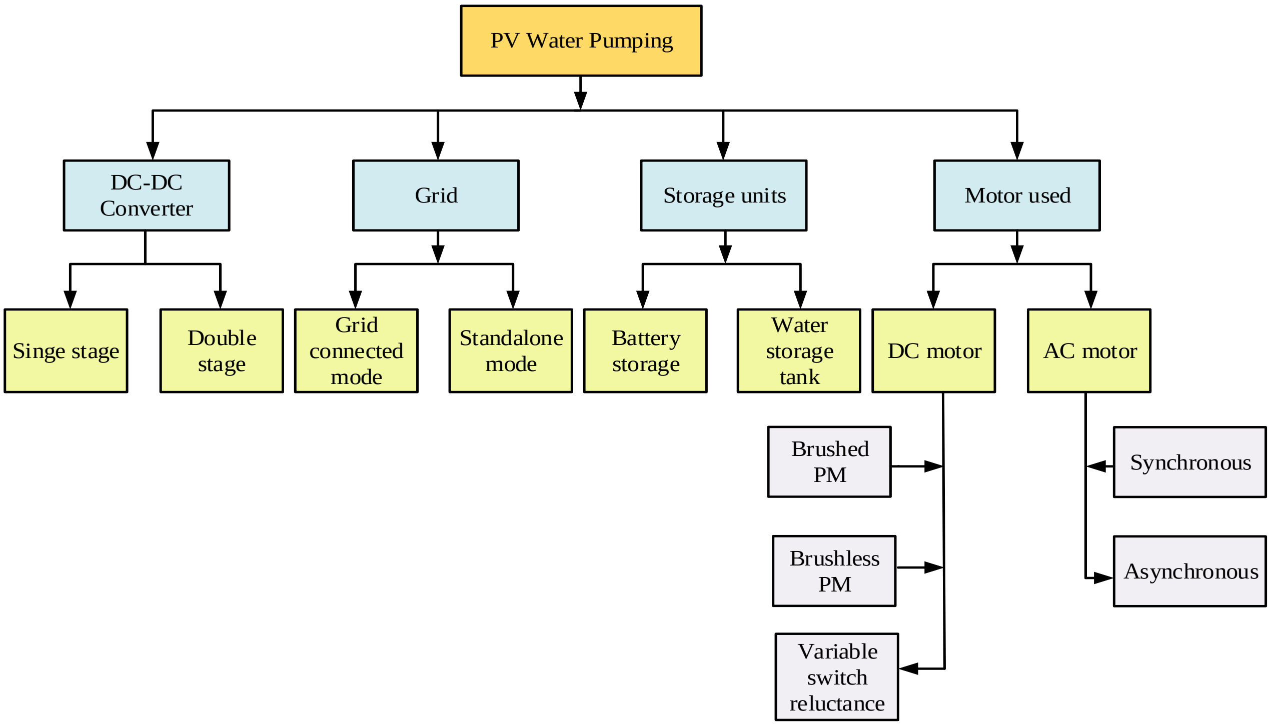

Fig. 1. Classification of PV water pumping system

drives aided PV pumping system. The various MPPT control techniques are discussed with subsets in section 3.The control topologies and drives for the water pumping system are reviewed in sections 4 and 5 respectively. The research contributions in terms of new MPPT technique and a new hybrid grid interactive PV system are presented in section 6. The conclusive remarks are given in section 7.

2. Solar PV Water Pumping System- State Of Art

The solar PV water pumping system (SPVWPS) is classified into different categories as shown in the figure 1. The broad classification is single stage and multi-stage; in single stage the DC-DC converter is not present, and the dc regulation is taken care of by the motor drive converter itself. However, in most applications DC-DC converter is employed for PV-source intermittency regulation. The two-stage conversion will incur more losses than the single stage. Another classification is with respect to grid interaction or standalone. The other classifications will be of storage unit usage and with the type of motor drive. Also, further classifications are based on the type of storage units used such as battery storage and water storage tank. The last one depends upon the type of motor used namely DC motors and AC motors. This converter-inverter is in control of either unidirectional or bidirectional power flow. This system operates in two modes namely, grid connected mode and islanded mode of operation. The former mode of operation is categorized into three different conditions. The first condition occurs when there is the absence of sunlight and there is a need for pumping operation. The pump will be operated from the supply taken from the grid. The second condition is when there is partial PV power i.e, the power produced by PV array is not sufficient to make the pump to run at rated speed.

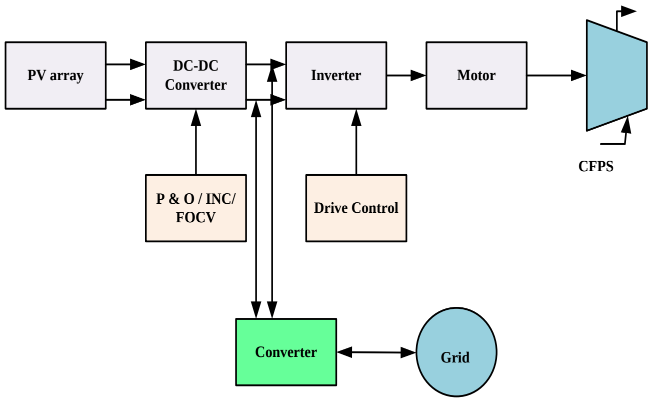

Fig. 2. Grid interconnected solar photovoltaic water pumping system

Here, the grid and the available PV power shares the power to drive the pump. In the third condition, there is no requirement for pumping operation while there is availability of solar irradiation, then the power generated by PV array is transferred to the grid. In the first and second conditions, the grid plays the role of source, while in the third condition the role of grid is the sink. The pump speed and the solar insolation intensity are proportional to each other. The basic block diagram of the grid-connected solar photovoltaic water pumping system is as shown in Fig. 2.

3. MPPT Techniques

To optimize PV array output power, the technique called MPP tracking has been used. The various MPPT techniques used in SPVWPS are discussed below.

3.1 P & O MPPT

There are several research articles archived pertaining to MPPT for PV systems under uniform irradiation. The P&O MPPT till date remains to be one of the most coveted and prevalently used technique[20]. In this technique the power is perturbed continuously in particular direction and checks whether the perturbation direction is towards the MPP. The direction of the perturbation can be changed depending upon the location of MPP. Researchers worked on the improvement of conventional P&O technique to overcome the inherent drawbacks it possesses in [21-22].

*3.*2 INC MPPT

This MPPT technique is known for its accuracy and oscillation free output power. This intelligent, fast and smart algorithm handles I/V and dI/dV for tracking MPP and hence the name INC MPPT.

3.3 Modified P & O

Most prevailing P&O MPPT's experience the deviation problem because of the varying insolation level [23-26]. To limit varying insolation levels, the affirmation of current characteristics of PV array must take in account for voltage in the PV array, which is pretty, much than zero. In any case, countless modified P&O MPPT strategies have been accounted for, as of late that appeared to accomplish high MPPT productivity.

3.4 Constant Voltage Tracking (CVT)

This MPPT is the simplest one which is also called as best fixed voltage method[27-28]. This technique operates on the basis of regulating PV module voltage depending upon its open circuit voltage. It consists of a voltage sensor for measuring the PV array voltage in order to set the converter's duty – cycle. At low irradiance conditions this method is more effective when compared to P&O and INC methods[29].

3.5 Over Voltage Tracking (OVT)

Under different irradiance and temperature, the open circuit voltage changes proportionally with MPP voltage[30] and its expressed as

$$V_{MPP} = K_{oc}V_{oc} \quad \text{where } K_{oc} < 1 \quad (1)$$

It is a simple method but choosing the optimal value for the proportionality constant Koc is difficult. The value of this Koc ranges from 0.73 to 0.80[31-35].

3.6 Short Circuit Tracking (SCT)

Due to change in irradiance the PV array's short circuit current modifies, with respect to this change MPP current also changes linearly. This linear equation can be mentioned as,

$$I_{MPP} = K_{sc}I_{sc} \quad \text{where } K_{oc} < 1 \quad (2)$$

In literatures[36-37], the value of the proportionality constant Ksc used are 0.94 and 0.92 respectively and for poly-crystalline its around 0.85[38-40]. Of the MPPT techniques, the P&O and the modified P &O are widely utilized for their exceptional performance in optimum utilization of PV power. The other control techniques are approximation techniques.

4. Inverter Control for WPS

The different methodologies required for inverter coupled motor drive control are reviewed in this section.

4.1 Field Oriented Control (FOC)

FOC is mainly implemented for the purpose of motor speed control. It works based on controlling both the magnitude as well as the phase of the input current and voltage of the motor. By using FOC in low speed operations better control performance is achieved by current controller's rotor flux controlling in d-axis without any implementation of stator flux estimator [41]. The three steps involved in the motor speed control are [21] , generation of reference speed, reference voltage vectors generation and VSI switching signal generation. The major merits of FOC are good torque response, control of torque at low speed and frequencies, dynamic speed accuracy, low consumption of power, small motor size and reduced cost.

4.2 Sliding Mode Control

This control method has the ability to control many uncertainties naturally, with robust nature and easy implementation. Due to these advantages, this control can be easily applied in different applications. It focuses on control by reducing the state trajectory to the surface sliding and the equilibrium point is achieved by developing it using some dynamic tuning parameters[42-44]. There are three parts in the trajectory namely[45].

- Choice of the switching surface
- Convergence condition
- Determining the law of control

Apart from its advantages, it has a drawback called as chattering effect, which occurs in the unmodelled dynamics presence with high frequency switching nature. This chattering effect can be avoided by applying continuous/smooth control signals[46].

4.3 Hysteresis Current Control

The torque ripple resulted due to commutation can be reduced by using hysteresis current control and also its implementation is very easy. This control technique has some merits like low cost, simple structure and requirement of memory abilities is little [47].

4.4 Direct Torque Control

In this method, the estimation of torque and magnetic flux can be done from the measured output of voltage and current of the motor. With the help of these values, we can directly control the motor torque and speed[48]. The improvement in performance of direct torque control technique occurs due to the advancement in artificial optimization methods, multilevel inverters and space vector modulation.

4.5 Fuzzy Logic Control

With the help obtained from mathematical models fuzzy logic, control can combine the information of a knowledgeable person[49]. Its structure can be modified depending upon components of internal configuration like fuzzy rules, fuzzification and defuzzification[50]. This control method is mainly used to reduce flux ripples and torque.

In general, these control techniques favor in controlling the speed and torque of motor, reduction in flux and torque ripples etc. Each of these control methods are exceptional with their features and are system adaptable. These are decoupled techniques that can be used even for higher power ratings.

5. Special Electrical Machines Driven Pumping System

The brief explanation about the special electrical machines, which are used in water pumping system, is discussed below.

5.1 PMSM Aided Pump Drive

Due to the advantages like low noise, compact size, improved efficiency, high power and high torque to inertia ratio, PMSM is suitable for SPVWPS applications[51]. By using field analysis, it is found that PM motor pumps are 20% more efficient than IM pumps[52]. At weak grid conditions, in order to make WPS system work satisfactorily, a Mix multi-resonant generalized integrator (MMRGI) is proposed[53]. In this paper, system cost is reduced by excluding the encoder. The power flow from grid is assisted by using the boost FEC converter, which also enhance the power quality at grid terminals[54]. The implementation of Hybrid multi-resonant generalized integrator-frequency locked loop (HMRGI-FLL) based control in grid connected SPVWPS has eliminated the distortion present in grid current and maintain the current THD within the identified limits, though the grid voltage gets distorted.The grid interfaced SWP driven by PMSM with Multi-resonant cascaded second order generalized integrator (MC-SOGI) dependent control structure efficiently eliminate the harmonic components as well as DC-offset when compared to conventional methods[55]. Here VSC is employed for the purpose of power flow in both the directions which fully utilizes the maximum capacity of SWP system. In this literature, sensor less vector control is applied for the speed regulation of PMSM which reduces the system cost and improves the reliability of the system. Grid current's THD is maintained as per IEEE-519 and IEEE-1547 standards. The speed control of PMSM has been implemented by sensor-less FOC[56].The bidirectional power flow control is achieved by using the unit-vector template (UVT), which provides some merits like low computational burden, low memory and less complexity. The schematic of PMSM driven solar photovoltaic water pumping system is as shown in fig. 3.

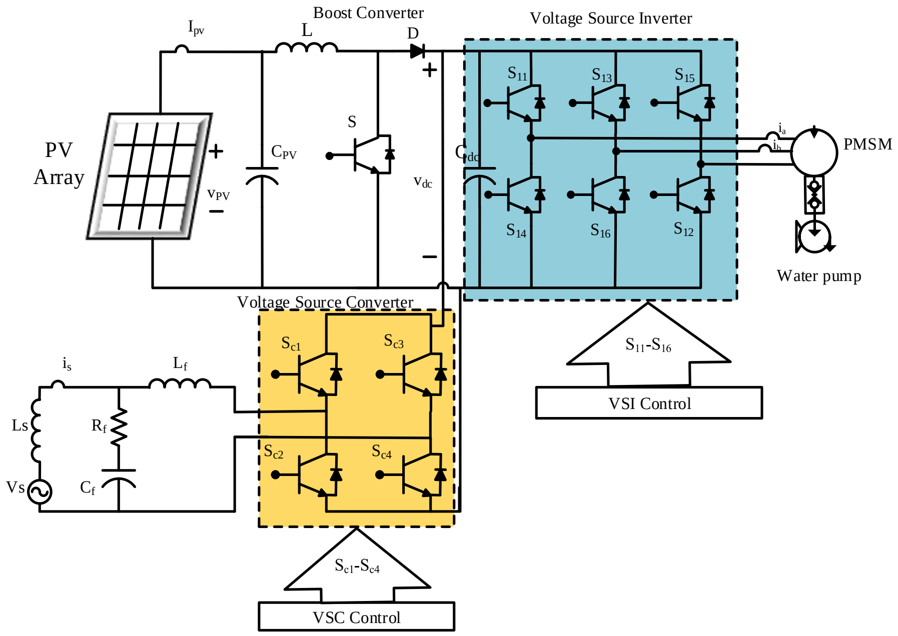

Fig. 3. Schematic of PMSM driven SPVWPS

5.2 BLDC Aided Pump Drive

BLDC motor is an energy saving system [57] and it has benefits like high efficiency, power density, power factor, improved capacity, compact size, no maintenance when compared to induction motor and reduces size and cost of PV panels installed [58-59].

The power sharing between PV array and grid in the grid connected SPVWPS driven by BLDC motor is controlled by unidirectional power flow controller through PFC boost converter [16]. BLDC motor's speed can be controlled by regulating the common bus voltage in the range of rated value. The grid connected BLDC motor driven SPVWPS is shown in fig. 4.

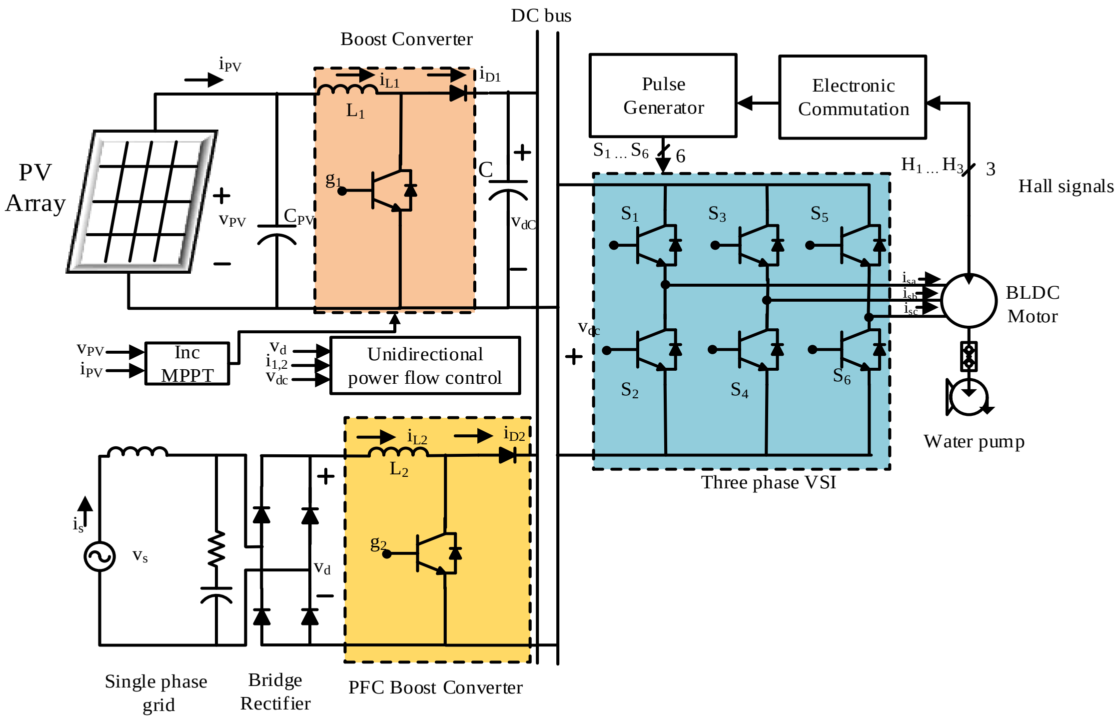

Fig. 4. Schematic of grid connected BLDC driven SPVWPS

Here the power flow is controlled by applying UVT generation technique[60].. Current sensing elements are not employed here. In order to enhance the efficiency, the switching losses are reduced by using fundamental frequency switching in VSI.

5.3 SRM Aided Pump Drive

The SRM drive is best suited for WPS without DC-DC converter due to its highly inductive nature. This drive is well suited for interfacing the grid with solar PV water pumping system due to its merits likegood efficiency, simpleand low cost power converter requirements [61-64]. This converter facilitates low switching losses, which improves the system efficiency up to 2–3% above the conventional scheme[63].

SRM driven grid connected SPVWPS with an improved generalized integrator-based grid side control algorithm has merits like rejecting the harmonic components and good DC offset [65], its schematic is shown in fig. 5. In this literature, feed-forward unit is combined with control technique to enhance the system performance and to reduce the burden on controllers. Here power quality aspects meet the IEEE-519 standard. The overall system efficiency is improved by commutating the converter with fundamental frequency while MPPT tracking done through VSC. For the rapid insolation change, modified P&O MPPT controller is used which maximize the PV array performance.

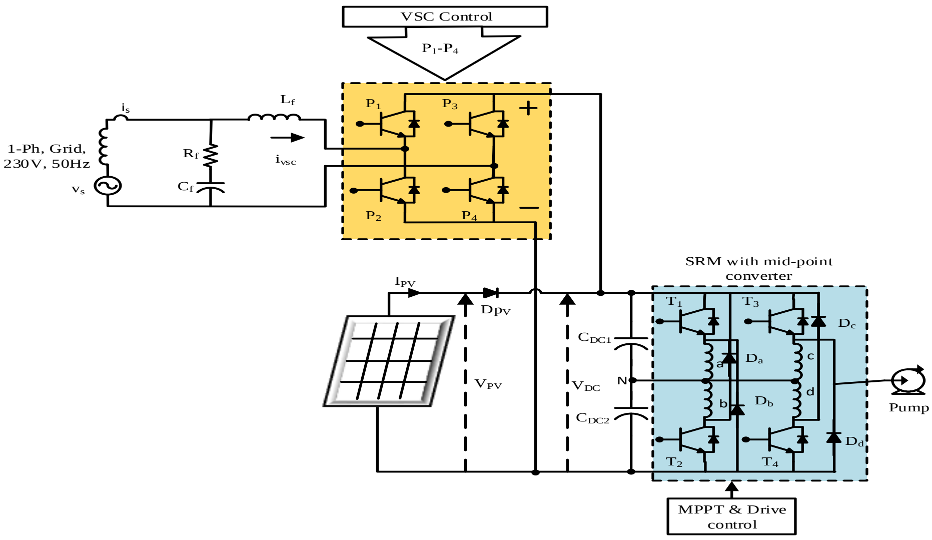

Fig. 5. Schematic of SPVWPS driven by SRM

5.4 SyRM Aided Pump Drive

The reluctance motors are characterized by simple construction and no rotor losses. For water pumping, among various reluctance motors SyRM is the best option . When compared to AC motors, SyRM's sensor less operation is much easier due to its anisotropic nature[66-67]. Elimination of rotor bar insertion makes this motor easier and less expensive from a manufacturing point of view. When compared to motors with permanent magnet, its cost is less and it is appropriate for power saving when compared to induction motors. This motor operates at synchronous speed, which makes the speed control simpler when compared to other AC motors and have a minimum rotor loss which leads to increased efficiency. The stator of SRM motor construction is same as that of the induction motor. Due to this result SRM motor can operate in all the three modes- say scalar, vector and direct torque controls either in the presence or absence of encoder [68]. PV fed three-phase SyRM is investigated through three approaches [69]. The first one focus on the starting current, the second approach deals with MPPT and the last approach on the specified voltage regulation. Among these approaches, the first and last results in the stable motor operation at rated conditions with 0.5 kW/m2 of insolation level. For these two approaches, the number of PV cells required is high, but second approach requires a smaller number of panels with high voltage regulation, which can be regulated by appropriate modulation index. In 3Φ grid connected SPVWPS driven by SyRM, the speed control of the motor is incorporated by using field-oriented control (FOC) scheme [70]. The schematic of this system is presented in figure 6. For the full utilization of resources and maximum capacity of water pumping, a bi-directional power flow control of VSC has been used. Boost converter at the side of PV array performs MPPT. Robustness and reliability of this drive gets enhanced by the speed sensor less operation.

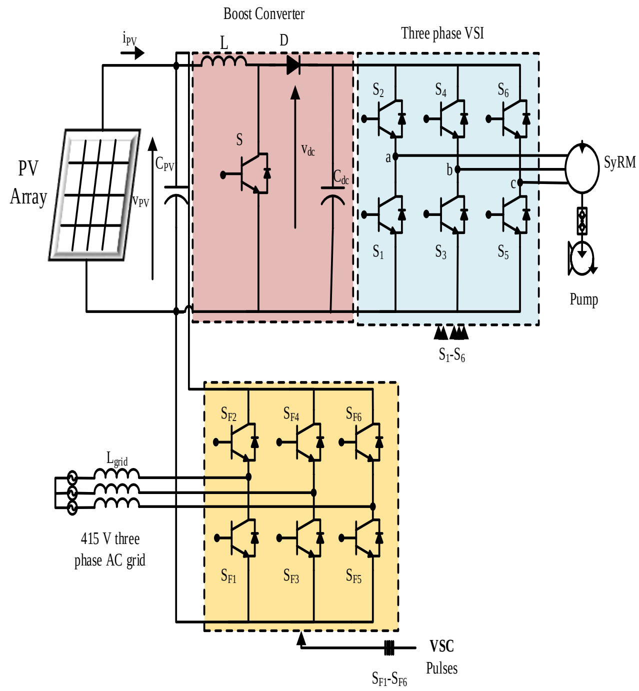

Fig. 6. Schematic of SyRM driven grid connected SPVWPS

Table 2 Characteristic comparison ofSEMs

Parameters	**Special Electrical Machines**			
	BLDC	PMSM	SRM	SyRM
Replacement	Brushed DC motor	AC Induction motor		Synchronous AC machine
Efficiency	High	High efficiency than BLDC	High	Low
Input current	Square wave current	Sinusoidal current	AC	AC
Stator windings	Concentrated	Distributed	Concentrated	Distributed
Back EMF	Trapezoidal	Sinusoidal	No	No
Control complexity	Easy	Complex	Complex	Complex
Cost	Lower	Higher	Low	High
Performance	Poor	High	High	Poor
Torque	Low	High	High	Low
Power density	Low	High	Very low	High
Overload capacity	Better than PMSM below 750W	Better than BLDC higher than 750W	Better than both PMSM and BLDC	Better
Torque ripple	Present	Absent	Present	Present
Acceleration	High at power below 500W	High at power above 500W	High	High
Size & weight	Light	Lighter	Heavy	Heavier
Manufacturing complexity	Easy	Complex	Easier	Complex
Noise	Low	Low	High	High
Application	Electric power steering, HVAC systems	Drivetrain of electric vehicles, aerospace, robotics	Electric vehicles, washing machines	Fans, pumps, web processing

The comparison of various special electrical machines based on their characteristics is shown in table 2. Double stage topological system has improved DC link voltage stability, flexible design and is easy to operate and control [65]. On comparing the power loss of the single and double stage grid connected photovoltaic systems [6], the overall loss factor is 0% for double stage and is 2.34% for single stage systems. The boost converter loss is 2.5% in double stage converter and is 0% in single stage systems. The losses in inverter are 2% in both of the systems.

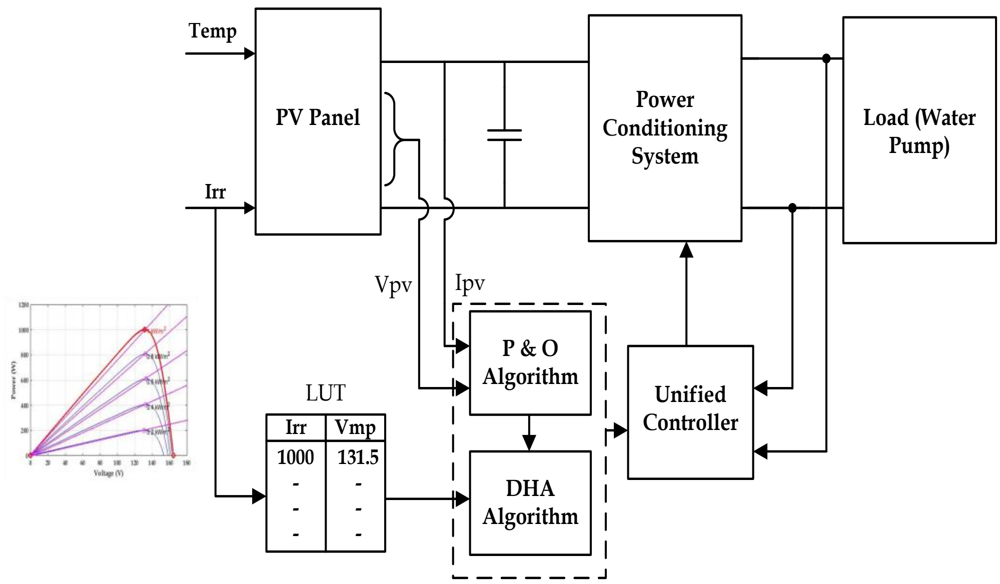

Fig. 7. Block diagram of the proposed Hybrid Grid interface WPS

6. Proposed Hybrid Grid Interactive Water Pumping System:

This paper apart from reviewing the research works related with special electric drives with water pumping system, proposes a new hybrid grid connected water-pumping system with a modified new MPPT tracking system. This section presents the operation of the proposed pumping scheme and the MPPT technique is presented in subsequent sections. The overall schematic diagram of the proposed research is presented in figure 7. Here the grid interactive and pumping system is realized as a blend of classical generator drive system with contemporary power electronic interfaces. The PV source is designed for a 1.5 KW power where in 6 x 250 W panels are connected in series. BLDC motor unit of 1kW, Impeller unit, MPPT controller, induction motor/generator set are the other necessary embodiments of the system.

6.1 Single Stage Conversion İn Water Pumping System

In single stage conversion WPS, there is no DC-DC converter which in turn reduces the losses, provides a compact and efficient system and has an added advantage of flexible voltage in the DC link subjected to PV power. The losses and the ripple current occurring in interfacing inductor depends on DC link voltage, whereas ripple content can be minimized by varying this DC link voltage. This system has better efficiency, small size and low cost because of the absence of the middle stage converter. When compared to double stage, single stage has somewhat lesser total loss.

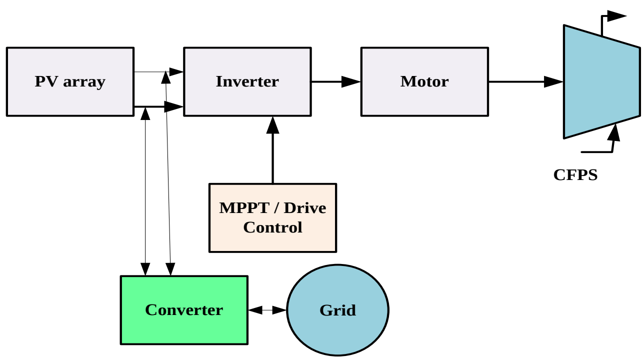

Fig. 8. Block diagram for single stage grid interconnected SPVWPS

The overall system efficiency of the single stage can be achieved higher when compared to double stage system by properly limit the operating voltage range6. The general block diagram for grid connected single stage WPS is presented in figure 8. Hence single stage conversion has been proposed in the water pumping system.

6.2 Proposed Direct Hunt Algorithm (DHA) MPPT

The description of direct hunt algorithm is discussed in this section. The algorithm is framed as an extension to P&O algorithm. In other words, it will complement the failure of P&O algorithm during abruptly varying irradiation condition.

6.2.1 DHA MPPT

The most prominent MPPT algorithm is well-entrenched MPPT algorithms available are perturb and observe (P&O) which is reliable and easy to execute. Here, a small incremental perturbation is introduced in the P-V curves and the search travels along the curve to find the peak of the curve for the given irradiation and temperature. If the power yield through the search is not progressive, then a change in the direction of search is introduced. On the other hand, the major drawback of (P&O) is even after grasping the peak, it tends to hover around the peak power which makes the system sluggish. P&O algorithm is hampered by drift problem during suddenly varying irradiation. During the search if the irradiation suddenly increases the power increases but the respective voltage for the new irradiation would have decreased, P&O algorithm inherently intends to drift towards the right wrongly. Therefore for abruptly varying irradiation P& O algorithm is not a better candidate. Hence, a new direct hunt algorithm (DHA) is cuddled along with the P& O algorithm.

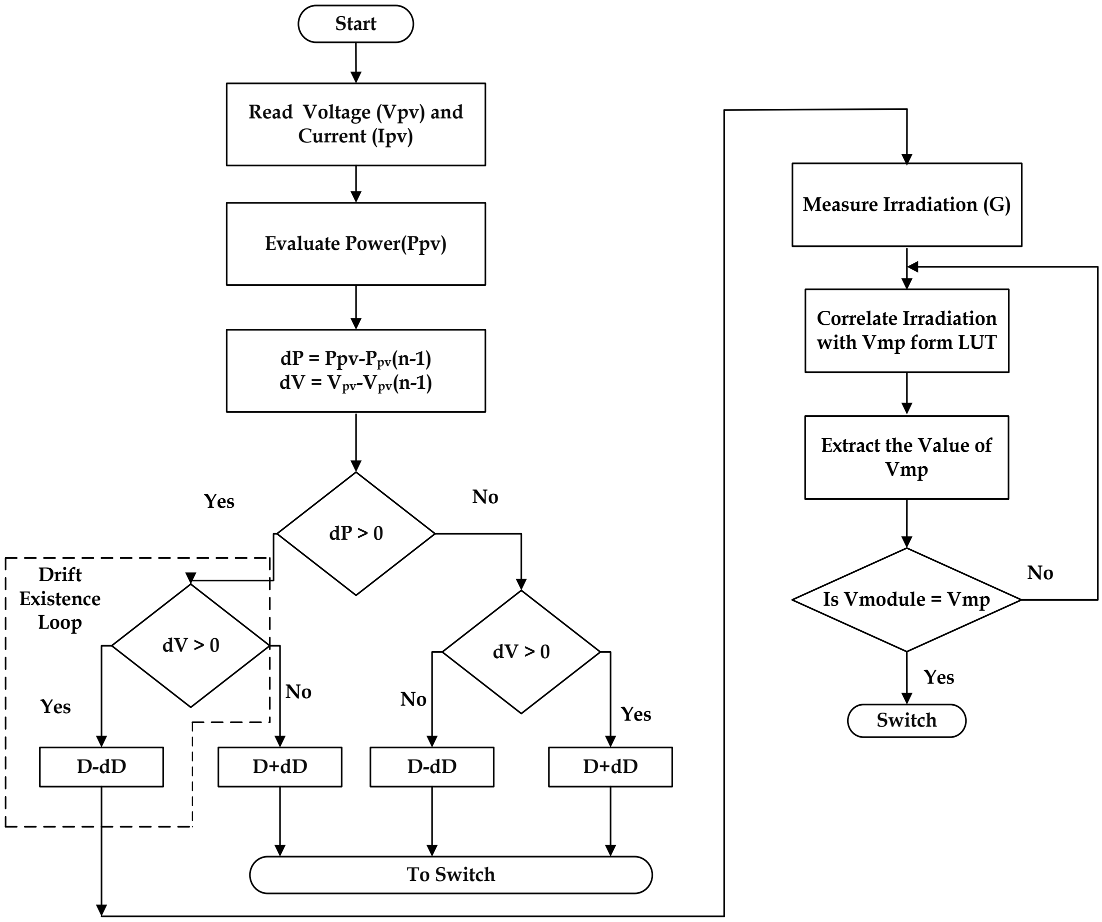

Fig. 9. Flowchart for DHA -MPPT

Direct hunt technique works with prior knowledge of the characteristic curves plotted for a given PV panel. A lookup table (LUT) is formed with datum of the Vmp for various irradiation values. An irradiation sensor replaces the costly current sensor, gives the irradiation value to the micro controller (processor) and the processor compares the operating voltage with the optimum Vmp and exert the control signal which makes sure the operation of PV panel at its peak power value. Figure 9 shows the algorithm for direct hunt –MPPT technique employed for utilizing optimum power from PV.

6.2.2 Control schemes of the proposed WPS

The proposed PV fed water pumping scheme has been dealt in three different cases. They are as follows.

Case 1: PV fed Water pumping:

The PV array feeds the BLDC drive through an inverter, which acts like an electronic commutator to switch and drive the BLDC to the stipulated speed. The shaft of the BLDC motor in turn is connected with the impeller unit which pumps the water. The block diagram is presented in fig. 10.

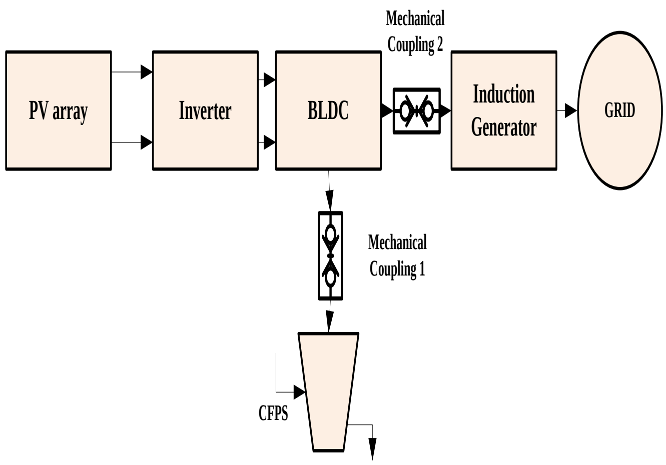

Fig. 10. Case 1 – PV fed water pumping

Case 2: PV array – BLDC – Induction generator and Grid

When water-pumping application is not required, the PV fed BLDC drive is connected to the shaft of the induction motor. The induction motor is made to run more than that of the synchronous speed and it acts like an induction generator and the power will pumped to the grid. Here the BLDC drive will behave like a prime mover. The excitation for the induction machine is acquired from the grid itself. This way is the simplest method of exporting generated power to the grid. The issues of complex grid interactive algorithms are completely negated in this approach. The functional block diagram of depicting this case is presented in figure 11.

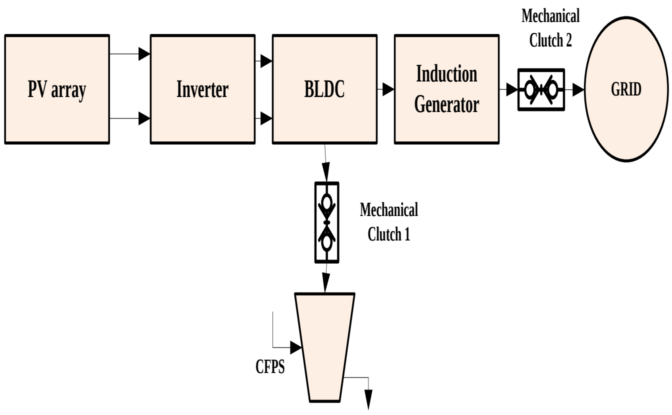

Fig. 11. Case 2 – PV array – BLDC – Induction generator and Grid

Case 3: Grid – Induction generator – BLDC and Pump

In this case, when water pumping is desperately needed when the photovoltaic power is not available, the drive is made possible by getting supply from the grid and the induction machine is made to run as an induction motor. The shaft of the induction motor is coupled with BLDC and on the other hand the BLDC is connected to impeller shaft. The block diagram of this case is presented in figure 12.

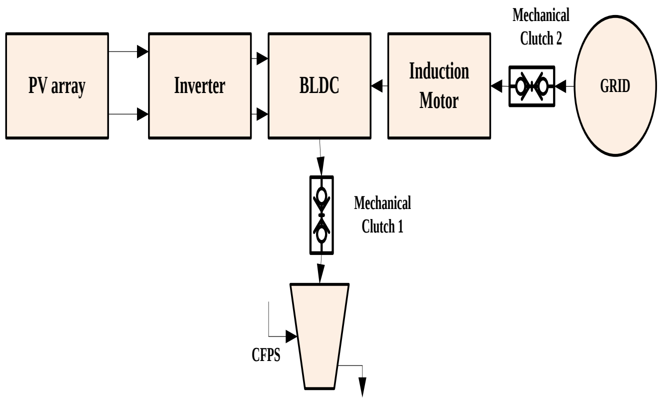

Fig. 12. Case 3 – Grid fed Water Pumping

The control schemes for the three cases discussed will be implemented through a controller. With necessary sensor arrangement, the controller deploys the flow diagram as given in figure 13.

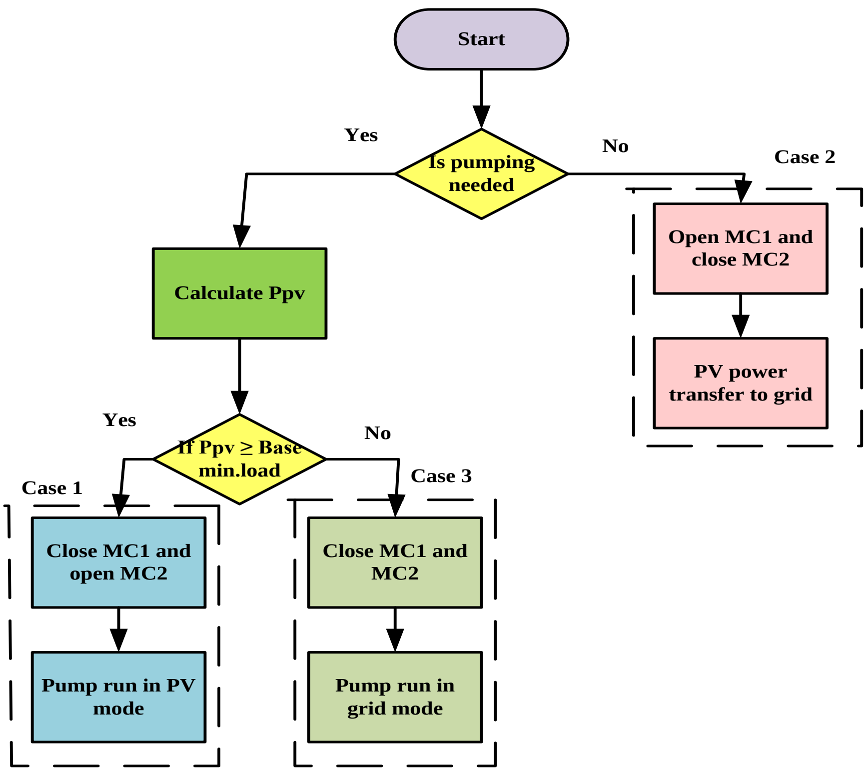

Fig. 13. Flow diagram for Hybrid Grid Interactive Water Pumping System

The hardware setup consists of a IGBT driven inverter drive, clutches, PV array input, induction motor and impeller.

Thus the proposed DHA-MPPT algorithm, the different control schemes of the water pumping system have been explained in section 6.

7 Results and Discussion

7.1 Simulation Results

The overall PV fed water pumping system has been simulated using MATLAB Simulink R2020a. Table 3 shows the comparison of PO –MPPT and the proposed Direct Hunt –MPPT techniques, at varying irradiation. The variation in voltage, current and power is observed form the table.

The simulation and hardware results of the proposed Direct Hunt MPPT is discussed in this section. It is also compared with the existing topologies.

Table 3. Simulation results for varying irradiation

S.No	Irradiance G (W/m^2)	P&O MPPT			Direct Hunt MPPT		
		V (Volt)	I (Amps)	P (Watt)	V (Volt)	I (Amps)	P (Watt)
1	1000	3.6-3.73	247-260	910 – 970	261.5	3.78	988.47
2	800	2.96-3.2	205-212	606.8 - 680	223	3.224	719

For a step change in irradiation , the corresponding response of voltage , current and power are shown in Figure 14.

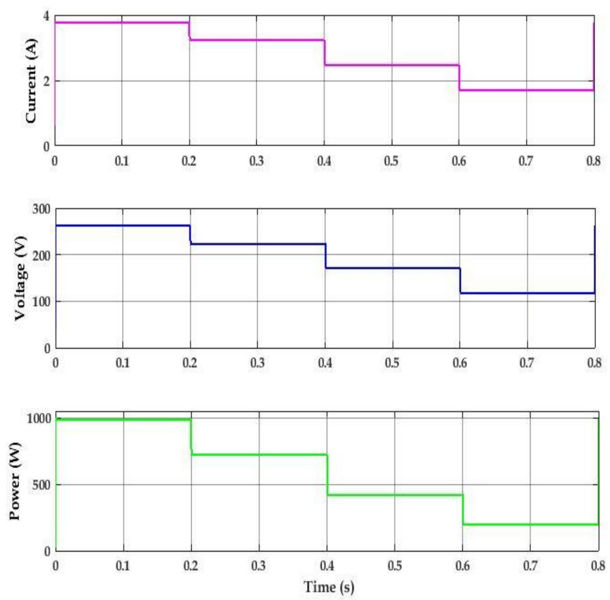

Fig. 14. Step change input

The water pumping system has been simulated in MATLAB by employing PO algorithm for comaprison with the proposed MPPT algorithm. From the current, voltage and power waveform curves of fig 16, it is observed that the curves are free from oscillation when the proposed DHA algorithm . The response of the system is not only swift but also overcomes the oscillation problem that prevails in P&O algorithm. The response through PO algorithm s shown in Fig 17. Figure 15 illustrates the relation between flow rate in m3/hr and speed in rpm. Based on affinity law,Q α n

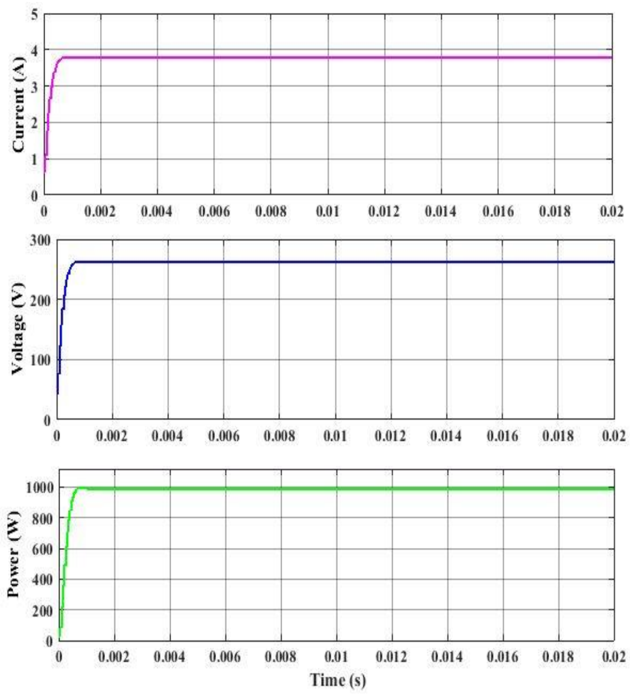

Fig.16. Output waveforms through DHA Algorithm

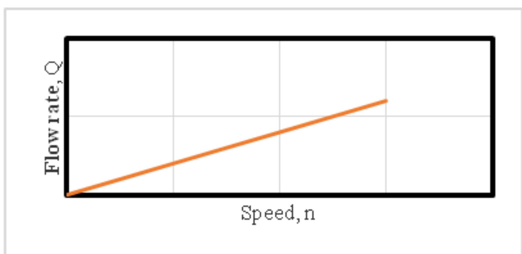

Fig. 15. Flow rate vs. speed curve

The relation between the flow rate and the speed has been explained through affinity law. According to this law, flow rate or capacity (Q) is directly proportional to the speed (n).

It can be observed that there are more oscillations in the output voltage and power waveforms in conventional PO MPPT.

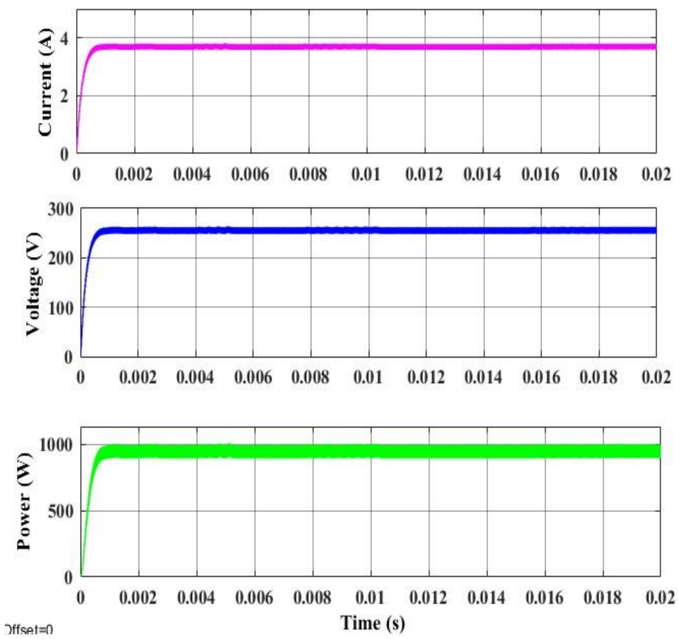

Fig. 17. Output waveforms through PO Algorithm

7.2 Hardware results

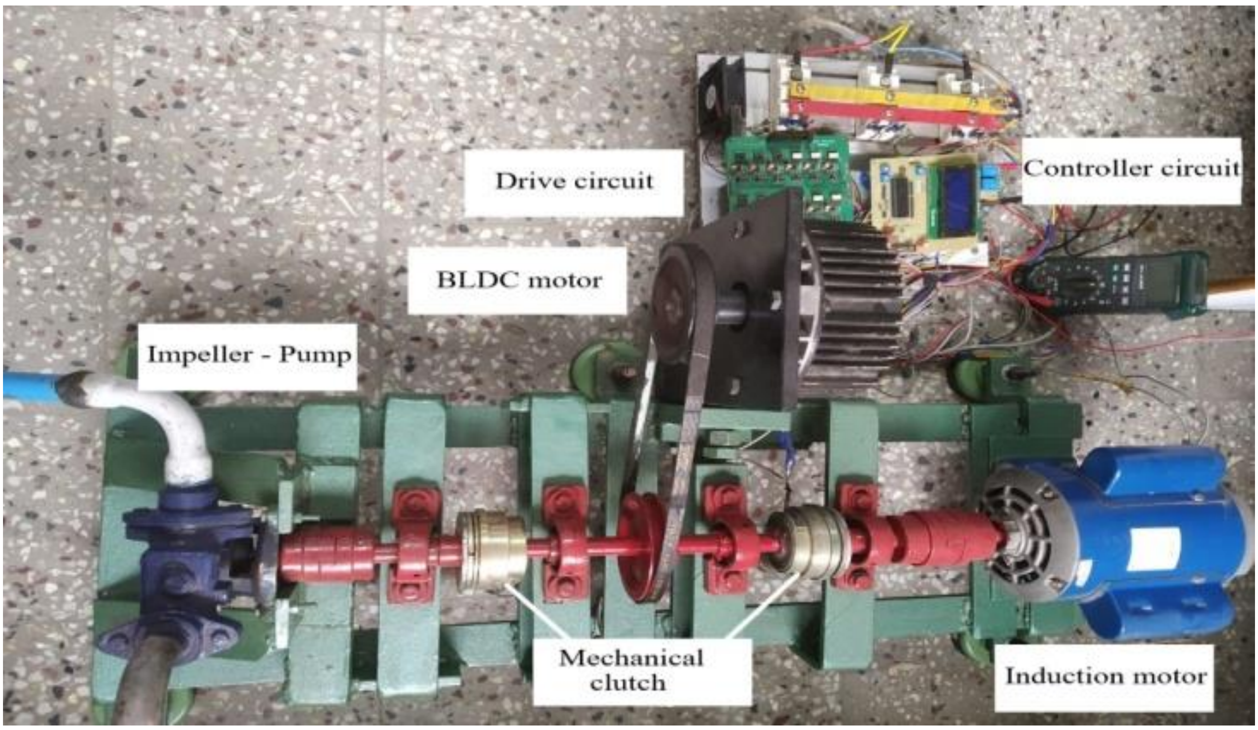

Fig. 18. Hardware setup of proposed system

The hardware setup of the proposed water pumping system is shown in figure 18. The real time hardware components are the controller circuit fed with PV, induction motor, BLDC motor, drive circuit, impeller pump and mechanical clutch.

The BLDC drive's performance is checked and the waveforms of stator back EMF, torque and speed are as shown in fig. 19.

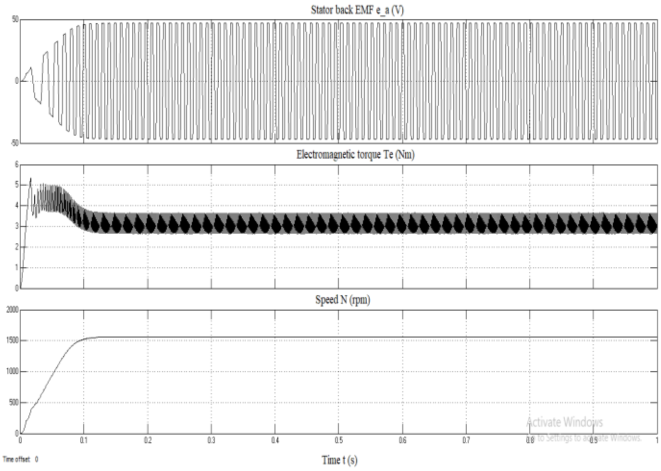

Fig. 19. Stator back EMF, torque and speed waveforms of BLDC drive

The output waveform of voltage and current for induction generator is shown in fig. 20.

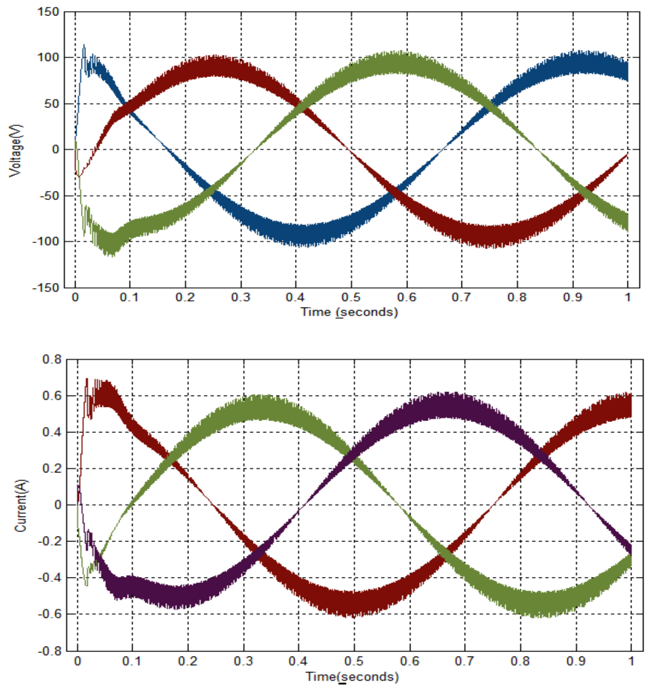

Fig. 20. Output voltage and current waveforms of induction generator

The hardware result of the proposed system is displayed in Table 4. The efficiency at varying irradiations are charted out in the table. The hardware results under the 3 control schemes that were briefed in section 6.2.2 have been shown here.

Table 4. Hardware result of the proposed system for all the cases

Case	**PV**				**BLDC**				**Induction generator**				η
	G (W/m^2)	V (V)	I (A)	P (W)	V (V)	I (A)	P (W)	N (rpm)	V_{rms}(v)	I_{rms}(A)	CosØ (θ)	P_{rms}(W)	(%)
1	1000	72	12	864	48	17	816	1500	-	-	-	-	94.44
	800	71.2	10	712	48	14	672	1500	-	-	-	-	94.38
	600	70.4	8	563.2	48	11	528	1500	-	-	-	-	93.75
	400	68	7	476	48	9.3	446.4	1500	-	-	-	-	93.78
2	1000	72	12	864	48	17	816	1500	230	3	0.99	683.1	79.06

	800	71.2	10	712	48	14	672	1500	230	2.45	0.99	557.87	78.35
	600	70.4	8	563.2	48	11	528	1500	230	1.94	0.99	441.74	78.43
	400	68	7	476	48	9.3	446.4	1500	230	1.6	0.99	364.32	76.54
3	-	-	-	-	-	-	-	-	230	4	0.99	910.8	-

The output power for the different irradiance level for both BLDC and induction generator is plotted in fig. 21.

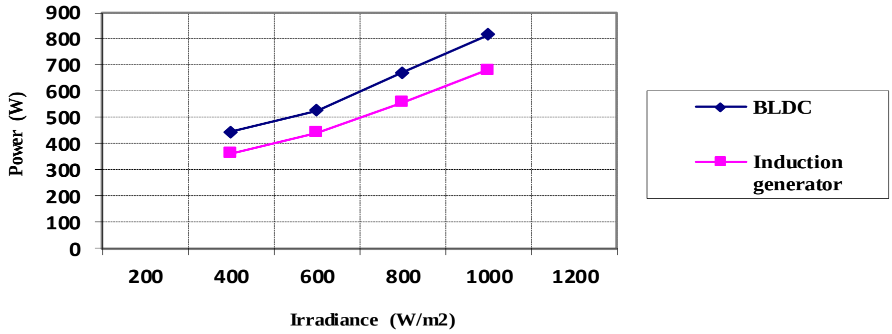

Fig. 21. Power Vs Irradiance curve for BLDC and Induction generator

The system efficiency for case 1 and 2 for various insolation level is as shown in fig. 23 (a) and (b).

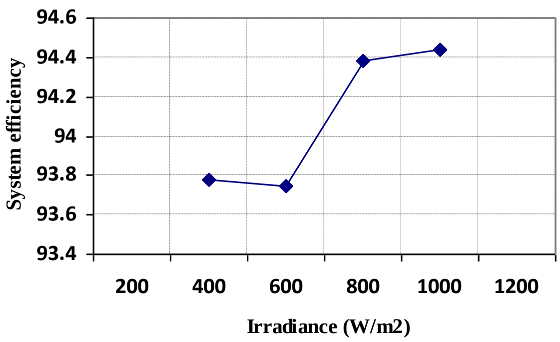

Fig. 22.(a). Case 1 -System efficiency at different irradiations

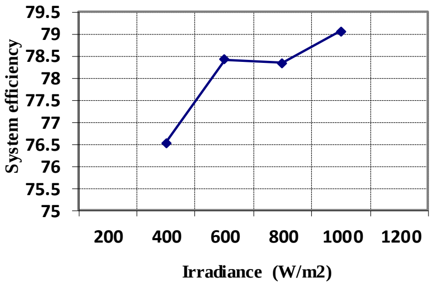

Fig. 22(b). Case 2-System efficiency at different irradiations

The comparison of different converter and control logic used in grid interacted SPVWPS is presented in table 5.

Table 5. Different SEM's comparison in grid connected SPVWPS

Authors [Ref.]	Motor type	MPPT Type	Speed control	Converter/Control Logic	Stage	Grid type
R. Kumar et al.[16]	BLDC	Incremental conductance	By regulating common bus voltage	Power Factor Corrected(PFC) boost converter (Unidirectional)	Double	1Φ
B. Singh et al.[19]	PMSM	P & O	Field Oriented Control (FOC)	Unit vector template theory	Double	1Φ
Shadab Murshid et al.[53]	PMSM	P & O	Sensorless Vector control technique	Vienna rectifier	Double	3Φ
Shadab Murshid et al.[54]	PMSM	Incremental conductance	Sensorless Vector control technique	Hybrid multi-resonant generalized integrator-frequency locked loop (HMRGI-FLL) control structure	Double	1Φ
Shadab Murshid et al.[55]	PMSM	Incremental conductance	Sensorless Vector control technique	Voltage Source Converter (VSC)	Double	3Φ
Rajan Kumar et al.[59]	BLDC	Incremental conductance	Continuously regulating the dc-bus voltage of VSI	Unit vector template generation technique	Double	1Φ
Anjanee Kumar Mishra et al.[64]	SRM	Modified P & O		Voltage Source Converter (VSC)	Single	1Φ
Anshul Varshney et al.[69]	SyRM	Incremental conductance	Field Oriented Control (FOC)	Voltage Source Converter (VSC)	Double	3Φ

8. Conclusion

This paper reviews the implementation of various special electrical machines like PMSM, BLDC, SRM, SyRM, etc., used for solar photovoltaic water pumping system. The research work demonstrated here proposes a new grid interactive water pumping system with BLDC drive and induction generator drive systems. Three key cases are considered and the power management between these cases are discussed in detail. Additionally, a new simple MPPT technique which is conducive for water pumping application is introduced in this work. The direct hunt MPPT scheme suggested here has 95 % efficiency and does not have any oscillations like its prominent counterpart perturb and observe MPPT. Also, the BLDC driven grid power injection does not possess power electronic switches which aggravates the harmonic presence. Also this research paper lays the platform for fellow researchers to refer to the previous body of research work on special electric machines fed water pumping system encouraging other prospects of PV water pumping research.

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