Comprehensive Review on Solar, Wind and Hybrid Wind-PV Water Pumping Systems-An Electrical Engineering Perspective

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***Abstract*—In India, the demand for water is continuously increasing due to the growing population. Approximately 16.5% of all country's electricity used to pump this water is from fossil fuels leading to increased pump Life Cycle Cost (LCC) and Green House Gas (GHG) emissions. With the recent advancement in power electronics and drives, renewables like solar photovoltaic and wind energy are becoming readily available for water pumping applications resulting in the reduction of GHG emissions. Recently, research towards AC motor based Water Pumping Systems (WPS) has received a great emphasis owing to its numerous merits. Further, considering the tremendous acceptance of renewable sources, especially solar and wind, this paper provides a detailed review of single-stage and multi-stage WPS consisting of renewable source powered AC motors. The critical review is performed based on the following figure of merits, including the type of motor, power electronics interface and associated control strategies. Also, to add to the reliability of solar PV WPS, hybrid Wind-PV WPS will be discussed in detail. Readers will be presented with the state-of-the-art technology and research directions in Renewable Energy-based WPS (REWPS) to improve the overall system efficiency and hence reduce the payback period.**

***Index Terms*—AC motor, hybrid wind-PV system, multi-stage solar water pump, pump life cycle cost, single-stage solar water pump, water pumping system.**

Nomenclature

ω	mechanical speed in rad/sec
G	Irradiance in W/m^2
H_1, H_2, H_3	Hall Sensor Signals
I_{AM}, I_{BM}	Line Currents (Motor pump) in Amperes
I_{PV}, V_{PV}	PV current in Amperes, PV Voltage in Volts
T	Temperature in Kelvin (K)
V_{AB}, V_{BC}	Line-Line Voltages (Motor pump) in Volts
V_{DC}	DC-link Voltage in Volts
AC	Alternating Current
APC	Active Power Control
AWPRC	Anti Wind-up Proportional Resonant Controller
BLDCM	Brushless DC Motor
CVC	Constant Voltage Control
DC	Direct Current
DMPPT	Distributed Maximum Power Point Tracking
DTC	Direct Torque Control
Exp.	Experimentation
FLC	Fuzzy Logic Control
FOC	Field Oriented Control
GAN	GAllium Nitride
GHG	Green House Gases
IC	Incremental Conductance
IDB	Interleaved Dual Boost
IM	three phase Induction Machine
LCC	Life Cycle Cost
MLUT	Modified Look-Up Table
MPPT	Maximum Power Point Trackin
MRAS	Model Reference Adaptive System
MTPA	Maximum Torque Per Ampere
OEIM	three phase Open End winding Induction Machine
P&O	Perturb and Observe
PCC	Point of Common Coupling
PMSM	Permanent Magnet Synchronous Motor
PTC	Predictive Torque Control
PWM	Pulse Width Modulation

Manuscript received October 14, 2019; revised February 29, 2020; accepted August 17, 2020. Date of publication March 30, 2021; date of current version March 16, 2021. This work was supported by the KLE Technological University - Hubballi, Karnataka, India, under capacity building project (CBP) scheme.

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Digital Object Identifier 10.24295/CPSSTPEA.2021.00001

Ref.	Reference
REWPS	Renewable Energy based Water Pumping System
SAZE	Sampled Averaged Zero Sequence Elimination
SEIG	Self Excited Induction Generator
SPWM	Sinusoidal Pulse Width Modulation
SPWPS	Solar Photovoltaic Water Pumping System
SRM	Switch Reluctance Motor
SVC	Static Voltage Compensator
SVPWM	Space Vector Pulse Width Modulation
SyRM	Synchronous Reluctance Motor
TCR	Thyristor Controlled Reactor
TIBC	Two Input Boost Converter
TLBO	Teaching Learning Based Optimization
VFD	Variable Frequency Drive
VSI	Voltage Source Inverter
WPS	Water Pumping System

I. Introduction

AGRICULTURE is one of the major contributors (17.2%) to Gross Domestic Product (GDP) of India, which is profoundly reliant on monsoons. Its contribution to GDP is found to be decreasing continuously due to uncertain rainfall. To fulfill the requirement of water, more than twenty million water pumps are installed in the country, which consumes approximately 92 billion units of energy per annum (22% of the country's electricity consumption). Most of the energy consumed (67 billion units of 92 billion units) to meet this water demand is generated using fossil fuels. Conventional WPSs driven by energy generated using fossil fuel result in increased GHG emission, leading to global warming. Also, they suffer other drawbacks like Motor burnouts, maintenance due to grid voltage variations, frequent power cuts/outages, Transmission, distribution losses and poor power quality of the grid. One solution to this problem is to explore the possibility of using renewable sources efficiently to meet energy demands. The continuous reduction in the cost of PV modules, the advancement in power electronics and computing technologies has attracted many researchers to innovate and provide efficient REWPSs.

The Life Cycle Cost (LCC) of a typical pumping system includes the cost of the motor pump, maintenance cost and the cost incurred for energy spent on pumping. More than 82% of the pumping LCC is due to energy utilized for pumping [1]. Thus, if the energy is not utilized effectively, it may lead to an increase in LCC of the pump, carbon footprint and GHG emissions. Moreover renewable energy sources like solar PV and wind energy are non-linear. Hence there is a need to employ appropriate power conditioning circuit and control strategy to extract maximum power from the chosen renewable source to ensure optimal LCC of REWPS. This firmly builds the motivation to investigate control strategies, power conditioning circuits, and motors used in REWPS for effective utilization of renewable energy sources.

So far, numerous review articles on REWPSs are published in literature. C. Gopal *et al*. [2] have identified solar PV, solar thermal, biomass, wind and hybrid wind-PV sources as five possible renewable energy sources that can be used to pump water. SPWPSs are dealt in greater detail with focus on system sizing. Authors have concluded that the solar PV, wind energy, and hybrid wind-PV systems are potential sources that will evolve with time for efficient and clean water pumping. P. Periasamy *et al*. [3] have studied classification of SPWPSs based on DC motor and AC Induction Motor (IM) driven systems. Focus in this study is on Electrical and Control Engineering perspectives like power converter stages, MPPT algorithms and microcontroller used for implementation. However, the investigations in this study are restricted to DC motor and AC IM only.

S. Chandel *et al*. have investigated several parameters like economic viability, pumping technology, performance analysis of installed SPWPS, sizing, degradation study, and efficiency improvement of SPWPS [4]. The research articles reviewed for efficiency improvement section are minimal. R. Rawat *et al*. have presented the detailed design procedure for standalone and grid-connected SPWPS [5]. Besides, authors have discussed on methods for size optimization and modeling techniques for a solar PV system. V. C. Sontake and V. R. Kalamkar [6] have framed SPWPS to be an interdisciplinary problem discussing challenges in fields like Mechanical, Electrical, Electronics, Computer, Control and Civil Engineering. Since the authors are addressing broad spectrum of challenges, the topics concerning types of motors and control algorithms are discussed in brief.

D. H. Muhsen *et al*. [7] studied design procedures, SPWPS modeling, field performance, reliability, system sizing, and control strategies. Authors have also reviewed some research articles based on control strategies concerning only DC motor based water pumps. S. Chandel *et al*. [8] have studied directly coupled SPWPS and also presented a case study (first of its kind) of 0.5 HP mono-block directly coupled dc motor pump in western Himalayan region of India. It is reported that directly coupled SPWPS suffer from under-utilization of solar PV power and need maximum power point tracking (MPPT) algorithm for effective utilization of solar PV power.

G. Li *et al*. [9] have investigated SPWPS with factors concerning system efficiency and optimization. Authors have also assessed performance of several installed SPWPS. In addition, the authors have presented cases of possible integration of solar PV with other green technologies like wind energy for water pumping applications.

It is evident from the reviews mentioned above that the overall system efficiency is dependent on many factors spanning various branches of Engineering. Many research avenues like system sizing ([4]–[7]), pumping technology ([4],[5]), economic viability ([6],[7]) and performance assessment ([7],[8]) are repeatedly examined with different perspectives. In Electrical Engineering, the power electronic interface, control strategies, and the type of motor pump significantly govern the efficiency of SPWPS. The afore-mentioned factors are investigated in [3] (for DC motor and IM only) and in [7],[8] (for DC motor only).

To date, there is no published research specifically consolidating the research avenues and work done in electrical engineering aspects of REWPS. This paper is an attempt to fill the void. This paper presents the review of control strategies for REWPS using AC motors. An exhaustive literature review will be presented on the following topics as the contributions of this paper.

- Multi-stage AC motor based SPWPS concerning the type of motor, power electronics interface, and control strategies for the overall system.
- Single-stage AC motor based SPWPS concerning the type of motor, power electronics interface, and control strategy for the overall system.
- Comparison of Multi-stage AC motor based SPWPS against single-stage AC motor based SPWPS.
- Wind energy based WPS concerning type of wind generator, power electronics interface, motor pump used and control strategy for the overall system.
- Hybrid wind-PV based WPS concerning the type of motor, power electronics interface, the generator for the wind turbine, and control strategies for the overall system.

It is to be noted that although discussions in this paper are focused towards the AC motor based WPS, the switched reluctance motor (SRM, a type of DC motor) is included for study under multi-stage and single-stage SPWPS due to the merits it offers.

II. Conceptual Background

A. REWPS

Water pumping is a process of imparting kinetic and potential energy to water to transfer it from one place to another. In REWPS, the renewable energy source is first converted to electric energy for use. A suitable power conditioning circuit with an appropriate control strategy is designed to efficiently deliver the available electric power to load (Motor coupled with centrifugal pump). The centrifugal pump coupled to the motor shaft helps to convert mechanical energy to kinetic and potential energy. Fig. 1 shows the subsystems of a typical renewable energy based water pumping system [10].

B. Classification of SPWPS

SPWPS has been the most desirable alternative to grid-connected and or diesel powered water pumps. Many innovations have ensued for the last four decades to utilize

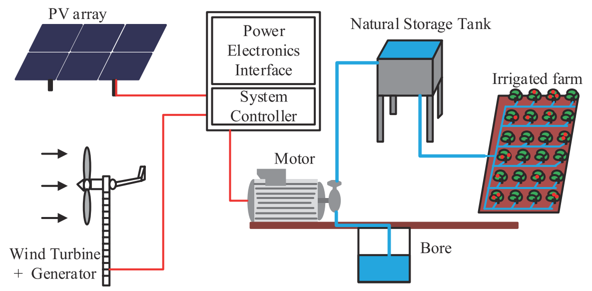

Fig. 1. Renewable Energy based Water Pumping System.

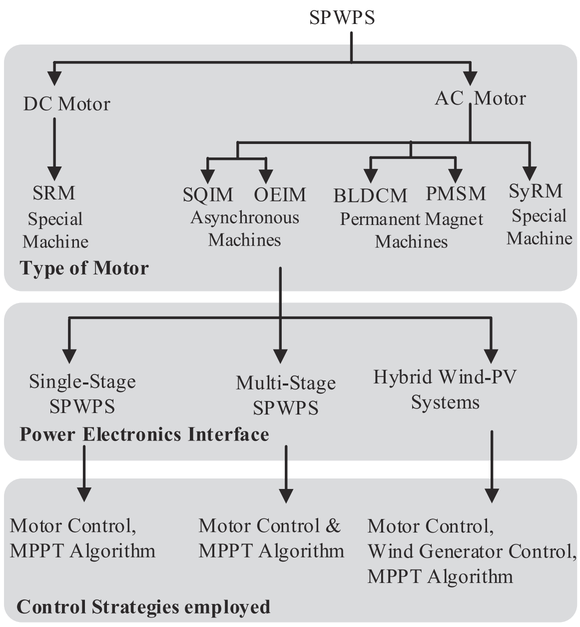

Fig. 2. Classification of Solar PV water pumping system.

the available power from the solar PV system effectively. In this section, an attempt is made to categorize the diversified research in SPWPS, as shown in Fig. 2.

The initial classification is based on the type of motors used for the pumping. In the early 1970's, DC motor pumps were more popular owing to the compatibility of solar PV power with the supply of the motor. However, with progress in power semiconductor technology, AC motors started gaining importance for pumping application over DC motors. AC motors are further classified as asynchronous machines, permanent magnet machines, and special electrical machines. SRM being DC motor is included for investigation due to its promising performance characteristics.

SPWPSs require power conditioning circuits to track maximum power from the PV source and to bring about compatibility between source and motor used. If the AC motor is employed in SPWPSs, power conditioning circuit is inevitable. Based on power conditioning stage/s between PV source and AC motor, SPWPSs are classified as single-stage SPWPSs and multi-stage SPWPSs which will be dealt in greater detail in section III and IV respectively. Recently Hybrid Wind-PV based WPS are gaining interest among researchers due to the stochastic nature

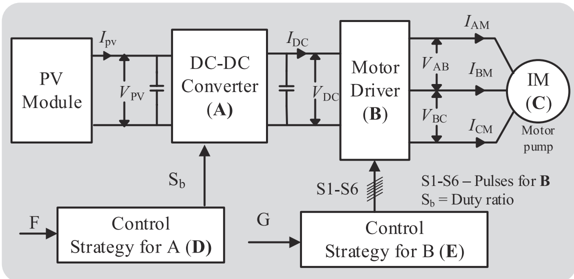

Fig. 3. Block level representation of Multi-stage SPWPS.

of the individual renewable source. Hence hybrid Wind-PV WPS is introduced as a third category of classification under the power electronics interface.

Finally, the control strategies employed for different power electronic interface and motor used for pumping are discussed. In single stage SPWPS, there is only one converter between source and load. Hence there can exist an algorithm for a converter to drive the motor or extract maximum power from the source. Lately, researchers have developed algorithms which can control motor and extract maximum power in single-stage SPWPS with some constraints on system variables and region of operation. Multi-stage SPWPS can house two or more converters for power conditioning between source and load. There exist multiple algorithms dedicated for maximum power extraction and motor control. In hybrid-wind PV WPS, an additional power converter and control algorithm may be required specific to the wind generator employed.

III. Multi-Stage SPWPS

Fig. 3 shows a generic block diagram of multi-stage SPWPSs which encapsulates research avenues namely DC-DC converter (A), motor driver (B), Motor (C), control strategy for A (D), control strategy for B (E), sensor inputs for D (F) and sensor inputs for E (G). Multi-stage SPWPSs consists of two power conditioning units between solar PV source and the motor pump. The first stage is meant for tracking maximum power from the solar PV source and typically a high gain DC-DC converter is used to step up the PV voltage. The second stage is employed for motor control and is specific to the motor used for pumping. Numerous motors are used for pumping namely Induction Motor (IM), Brushless DC Motor (BLDCM), Permanent Magnet Synchronous Motor (PMSM), Synchronous Reluctance Motor (SyRM), Open-End Winding Induction Motor (OEIM) and SRM. In this section, the literature for each of the motor pump is presented in particular.

A. IM Based WPS

IM is a popular choice for water pumping due to it's low cost, rugged construction, ease of availability in local market, reduced maintenance and inherent short circuit protection. The research in speed control of the IM is broadly classified into scalar and vector control algorithms.

1) Scalar Control

Scalar control is the simple control algorithm employed for speed control of IM below rated speed.

Y. Yao *et al*. [11] have implemented square wave drive mode with frequency control to improve the performance of SPWPS. A simple MPPT algorithm using Constant Voltage Control (CVC) is employed using boost converter. The system is compared with conventional fixed frequency motor drive for efficiency improvement. B. Kumar *et al*. [12] have employed Fixed frequency drive to run the IM at rated speed at all times. Performance of three MPPT techniques are compared in the study, namely Incremental Conductance (InC), CVC and Fuzzy Logic Control (FLC). The proposed FLC is reported to perform superior to the other two algorithms. The DC-link voltage control is not evidenced. Hence the system is vulnerable to flux saturation under varying insolation conditions.

B. Pakkiraiah *et al*. [13] have used Space Vector Modulation (SVM) to regulate the DC-link voltage and control the speed of the IM pump. Direct duty ratio based MPPT algorithm is employed using a boost converter for increased stability. The energy utilization and efficiency are reported to increase due to the applied control strategy.

M. Akbaba [14] has studied the VSI operating at a fixed frequency to run the motor at rated speed. Interleaved Dual-Boost (IDB) converter is employed to reduce the input current ripple. For the system under test, the duty ratio for IDB is empirically fixed as 0.46 to extract maximum power and maintain DC-link voltage constant. The DC-link voltage is considered to be fixed assuming negligible voltage variations in the PV voltage for varying insolations. It is concluded in the paper that proper matching of pump to the solar PV source can lead to simple control strategy while utilizing maximum energy.

J. V. M. Caracas *et al*. [15] have proposed a Two-Inductor Boost Converter (TIBO) for high voltage gain and low input current ripple. Standard V/F based Sinusoidal Pulse Width Modulation (SPWM) is implemented for VSI fed IM pump. The proposed system is reported to be tested for the commercial water pump and is said to exhibit satisfactory performance.

B. Singh *et al*. [16] have discussed a simple control strategy for IM pump with a reduced number of sensors. The boost converter is used to track MPP using InC algorithm. A control strategy using pump affinity law which inherits pump constant is proposed to increase the stability of the system.

Considerable effect of partial shading on SPWPS is studied by A. Mudlapur *et al*. [17]. The consequences of effects like high varying panel voltage and transients in the DC-DC converter on the overall system is presented.

C. Jin and W. Jiang [18] have presented a power converter consisting of high gain DC-DC converter and PWM-VSI. Complimentary PWM with MPPT and Space Vector Pulse Width Modulation (SVPWM) are employed for DC-DC converter and PWM-VSI respectively for application in the nano filtration system.

2) Vector Control

Vector control of IM drive is a high-performance algorithm which transforms three-phase stator currents to orthogonal quantities. One of these quantities represent magnetic flux and the other represents torque component of the motor. Vector control algorithm though complicated to implement, offers specific merits like a fast transient response and improved life expectancy of the system. With the advancement in power semiconductor technology and availability of high-speed microcontrollers, the vector control algorithms for IM control are becoming a viable option over scalar control methods.

V. Vongmanee [19] has presented Field Oriented Control (FOC) to regulate the DC-link voltage of the VSI by sensing, the line currents, DC-link voltage and the shaft speed of the motor. The ratio (I_{ds}/I_{qs}) is maintained to an optimal value to operate the motor pump at maximum efficiency for all the insolation levels. The proposed algorithm is reported to give a better transient response in comparison with the scalar control algorithm. S. G. Malla *et al*. [20] have presented a multimachine irrigation system using VSI fed IM pump. Conventional P&O algorithm is used to extract maximum power using boost converter. DC-link voltage of the VSI is maintained constant with changing insolation by employing vector control algorithm to match the available solar PV power with load. An effective method of pumping in absence of battery is demonstrated with multiple pumps at place. M. Arrouf *et al*. [21] have investigated primitive Indirect FOC (IFOC) algorithm using line currents and speed. The system results in under utilization as no algorithms are employed for maximum power extraction. M. Errouha *et al*. [22] have proposed IFOC with loss minimization and MPPT algorithm as an improvement to [21], leading to enhanced energy utilization.

A. Chikh, A. Chandra and S. Singh, B. Singh have proposed pump affinity laws to derive the reference speed for each insolation in [23] and [24] respectively. The error in speed is processed by forcing appropriate currents hence optimizing the pump flow rate. P&O algorithm is used to generate pulses for boost converter to extract maximum power. A satisfactory steady state and dynamic performance for varying insolations is reported using pump affinity laws. M. A. Vitorino *et al*. in [25] have made vital contributions like the design of high gain Push-Pull DC-DC converter and efficient optimization algorithms for IM pump. The authors have exhaustively investigated vector control algorithms in addition to efficiency optimization of IMs and have concluded that IFOC with power factor optimization yields optimal results.

B.Talbi *et al*.[26] have presented battery-less SPWPS employing P&O algorithm with variable step-size for MPPT, Predictive torque control (PTC), flux control to control IM drive, A fuzzy logic controller (Takagi-Sugeno type) is developed to regulate the DC-link voltage. The overall control strategy is reported to provide reduced torque ripple and improved torque response.

Active Power Control (APC) with the Anti-Windup Proportional Resonant Controller (AWPRC) for AC voltage regulation proposed by M. Rezkallah *et al*. in [27]. The overall strategy though complicated results in enhanced energy extraction, improved power quality, and better transient response for SPWPS.

S. Shukla and B. Singh have proposed Direct Torque Control (DTC) for IM pump with a novel Model Reference Adaptive System (MRAS) technique [28]. The proposed MRAS technique eliminates the speed sensor. The proposed MPPT algorithm is equipped with an additional loop to control the flow rate of the pump. Adaptive parameter estimation is incorporated to overcome the changes in motor parameters due to temperature variation. Further, an improvement to [28] is proposed in [29] by eliminating voltage and current sensors, making the overall system more stable.

The commercially available solar pumping system [30] shows the usage of scalar control algorithms ([11]–[18]) using SVPWM control strategy. Despite the improved efficiency and the transient response, the vector control algorithms ([19]–[25]) are not popular because they demand information on machine parameters like resistance, inductance, and flux. Hence vector control algorithms are yet to evolve for commercial usage.

B. BLDCM Based WPS

Permanent magnet motors although expensive, offer merits like high efficiency, power density and superior power factor of operation. Hence few researchers have ventured in exploring the capabilities of BLDCM for water pumping.

A. Terki *et al*. in [31] have compared CVC and Fuzzy rule-based algorithm for MPPT using boost converter. The MPP is also used to define speed reference for the motor pump. The reference currents are generated by using speed and position information of the motor. The error in speed is further processed using hysteresis controllers and FLC. The proposed FLC is reported to yield better dynamic response in comparison with the conventional hysteresis controller. Similar work is carried out by E. E. A. Zahab *et al*. [32] with experimental validation and a battery backing system as additional contributions.

B. Singh and R. Kumar have exhaustively carried out investigations on BLDCM based water pump[33]–[36]. The speed of the motor pump is controlled by varying the DC-link voltage based on changes in solar insolations. Only hall sensor signals are read as feedback signals, no information regarding DC-link voltage or line currents are captured for control. The authors have carried out extensive research in MPPT tracking using Landsman converter [33], Buck-boost converter [34], Zeta converter [35] and Cuk converter [36] leading to reduced filtering requirements, unbounded region for MPPT, improved results under low insolation and non-pulsating currents respectively. Further an improvised sensor-less control algorithm for BLDCM based pump is proposed in [37].

C. PMSM Based WPS

In addition to merits offered by BLDCM, PMSM offers high efficiency and lower torque ripple. Some researchers have chosen PMSM as a potential alternative for water pumping application.

F. Maissa *et al*. [38] have proposed an algorithm for maximum power extraction by employing sliding mode control to boost converter. The maximum power point is also used to generate the reference speed for the PMSM pump. The error in speed is processed using Current Controlled VSI (CCVSI) driving PMSM pump. H. Bouzeria *et al*. [39] have developed a Fuzzy logic technique which tracks maximum power against source and load variations using boost converter. The MPP defines the operating speed of PMSM pump, which is regulated using DTC algorithm. Vector control algorithms are invariably chosen in [38] and [39] to increase the life expectancy of the motor, speed range, and efficiency.

D. SyRM Based SPWPS

M. Nabil *et al*. [40] have proposed a simple control strategy for performance enhancement of SyRM SPWPS. The controller achieves successful motor starting, regulates the voltage using V/F control and extracts maximum power from solar PV for insolation above 0.5 sun.

E. SRM Based SPWPS

In comparison to asynchronous and permanent magnet motors, the SRM offers high efficiency, high torque at a lower cost due to its core construction. Hence, it qualifies as a potential alternative for water pumping application [41], [42].

H. M. Metwally and W. R. Anis [43] have studied a two-stage SRM drive for water pumping application. The first stage of power conversion regulates the battery charge for continuous water pumping.The drive circuit (second stage) proposed for SRM is simpler than PWM-VSI, and the efficiency of the proposed system is reported to be better than its equivalent DC and AC induction machine.

V. Narayana *et al*. [44] have studied the Canonical Switching Cell (CSC) converter to reduce the cost of the SRM based pump system. The continuous conduction mode of operation of the CSC converter is reported to reduce the stress on system components. Furthermore, the fundamental switching scheme of a mid-point converter results in reduced losses increasing the system efficiency.

A. K. Mishara and B. Singh [45] have proposed a Single Input Dual Output (SIDO) converter for SRM based SPWPS. The proposed converter is derived from Zeta and Landsman converter ensuring maximum power extraction from solar PV source and soft starting of SRM based WPS. Furthermore, Optimal energy extraction and soft starting feature are added by replacing SIDO converter with dual boost converter [46] and Luo converter [47] along with mid-point converter. The proposed topology results in increased efficiency, compactness, reduced cost and reduced sensor count as compared to [43].

F. Summary

Multi-stage SPWPS encapsulates a wide range of research avenues (with columns A to G) as summarized in Table I. The research in multi-stage SPWPS can be broadly classified into MPPT algorithms and motor control algorithms. The variety is observed in MPPT tracker (A), motor used for water pumping (C), MPPT algorithms (D), motor control strategy (E) and sensors used for motor control strategy (G).

A high gain DC-DC converter is chosen as MPPT tracker to match the PV voltage to the DC-link voltage. Referring to Table I, it is evident that the motor driver chosen is VSI for all the motors except SRM. Perturbation based MPPT algorithms like P&O and InC have been popular among researchers; however, few intelligent algorithms based on Fuzzy logic are also implemented for improved efficiency. The motor control algorithms can be broadly classified into scalar and vector control algorithms. Scalar control is simple to implement and involves PWM techniques like SPWM and SVPWM. Vector control algorithms are classified into direct and indirect control based on the presence and absence of the speed sensor. Furthermore, vector control involves intensive computation, knowledge of machine parameters, and additional sensors and hence are not a preferred choice for commercial use. The sensors used for the MPPT algorithm are PV voltage and current (V_{PV} & I_{PV}) in most of the research. However, the sensors used for the motor control algorithm depends on the type of the algorithm (scalar or vector control) and the motor used for water pumping.

IV. Single-Stage SPWPS

Fig. 4 shows the generic block diagram of single-stage SPWPS. WPS with minimal (only one) stage of power processing unit between solar PV and AC motor pump is classified as single-stage SPWPS. It is evident from the Fig. 4 that MPPT tracker (A) and the associated algorithm (D) are eliminated in single-stage SPWPS. Hence, the research avenues in single-stage SPWPS includes the motor driver (B), Motor (C), the control strategy for B (E) and sensor inputs for E (G).

A. IM Based SPWPS

1) Scalar Control Algorithms

E. Muljadi [48] first attempted MPPT algorithm with AC motor based systems, A system of VSI along with IM is modeled as frequency dependent variable resistor. Frequency is suitably controlled to track MPP to utilize available energy from PV source efficiently. The square wave drive is used for inverter in place of PWM to reduce the switching losses. A. Raju *et al*. have proposed SVPWM technique to match the available maximum PV power to load power. The switching losses are said to be minimal due to the advancement in semiconductor technology.

P. Packiam *et al*. [50] have conducted experiments using three volts/hertz based control strategies namely square wave drive, SPWM, and SVPWM with P&O as standard MPPT algorithm. It is concluded in the study that, SVPWM with P&O algorithm gives best results with fast transient response,

TABLE I
SUMMARY OF MULTI-STAGE SPWPS

Ref.	MPPT Tracker (A)	Motor Driver (B)	Motor (C)	MPPT Algorithm (D)	Control Strategy (E)	Sensors for D (F)	Sensors for E (G)	Exp.
[11]	Boost C.	VSI	IM	P&O	Frequency control	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, V_{AB}, V_{BC}$	Yes
[12]	Boost C.	VSI	IM	FLC based MPPT	SPWM	I_{PV}, V_{PV}	V_{DC}	No
[13]	Boost C.	VSI	IM	Modified P&O	SPWM	I_{PV}, V_{PV}	None	Yes
[14]	IDB C.	VSI	IM	Fraction Voltage algorithm	SPWM	V_{PV}	None	Yes
[15]	TIBO	VSI	IM	Hill Climbing algorithm	SVPWM	I_{PV}, V_{PV}	V_{DC}	Yes
[16]	Boost C.	VSI	IM	InC	SPWM	I_{PV}, V_{PV}	V_{DC}	Yes
[17]	Boost C.	VSI	IM	P&O for partial shading	SVPWM	I_{PV}, V_{PV}	V_{DC}	Yes
[18]	Frontend C.	VSI	IM	P&O	SVPWM	I_{PV}, V_{PV}	V_{DC}	Yes
[19]	Boost C.	VSI	IM	P&O	Maximum efficiency algorithm using vector control	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, V_{AB}, V_{BC}$	Yes
[20]	Boost C.	VSI	IM	P&O	Power & Voltage based vector control	–	$I_{AM}, I_{BM}, V_{AB}, V_{BC}, V_{DC}, N$	No
[21]	Buck C.	VSI	IM	–	IFOC	–	I_{AM}, I_{BM}, N	No
[22]	Boost C.	VSI	IM	P&O	IFOC with loss minimization	I_{PV}, V_{PV}	I_{AM}, I_{BM}, N	No
[23]	Boost C.	VSI	IM	P&O	Sensorless vector control	I_{PV}, V_{PV}	I_{AM}, I_{BM}	Yes
[24]	Boost C.	VSI	IM	Modified P&O	SPWM	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, V_{AB}, V_{BC}$	No
[25]	Push-pull C.	VSI	IM	P&O	IFOC Combined with balancing current	I_{PV}, V_{PV}	I_{AM}, I_{BM}, V_{DC}	Yes
[26]	Boost C.	VSI	IM	Current based P&O	Predictive torque & Flux controller	I_{PV}, I_S	I_{AM}, I_{BM}	Yes
[27]	Boost C.	VSI	IM	Power ratio variable step algorithm	Active power based AWPRC controller	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, V_{AB}, V_{BC}$	Yes
[28]	Boost C.	VSI	IM	Drift free P&O	MRAS based DTC	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, V_{AB}, V_{BC}$	Yes
[29]	Boost C.	VSI	IM	Modified P&O	Indirect FOC (speed, voltages and current estimation)	I_{PV}, V_{PV}	V_{DC}, I_{DC}	Yes
[31]	Boost C.	VSI	BLDCM	FLC	FLC	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, H_1, H_2, H_3$	No
[32]	Boost C.	CCVSI	BLDCM	FLC	FLC	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, H_1, H_2, H_3$	No
[33]	Landsman C.	VSI	BLDCM	InC	DC-link Voltage Control	I_{PV}, V_{PV}	H_1, H_2, H_3	Yes
[34]	Buck-Boost C.	VSI	BLDCM	InC	DC-link Voltage Control	I_{PV}, V_{PV}	H_1, H_2, H_3	Yes
[35]	Zeta C.	VSI	BLDCM	InC	DC-link Voltage Control	I_{PV}, V_{PV}	H_1, H_2, H_3	Yes
[36]	Cuk C.	VSI	BLDCM	InC	DC-link Voltage Control	I_{PV}, V_{PV}	H_1, H_2, H_3	Yes
[37]	Boost C.	VSI	BLDCM	InC	Sensorless Line-voltage Control	I_{PV}, V_{PV}	V_{AB}, V_{BC}	Yes
[38]	Boost C.	VSI	PMSM	P&O	SMC	I_{PV}, V_{PV}	I_{AM}, I_{BM}	No
[39]	Boost C.	VSI	PMSM	FLC	FLC based DTC	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, V_{AB}, V_{BC}, N$	No
[40]	Boost C.	VSI	SyRM	P&O	Soft-start voltage control	I_{PV}, V_{PV}	V_{DC}	No
[43]	Battery Voltage regulator	SCR based driver	SRM	on-off control	SRM drive Controller	I_{PV}, V_{PV}	$I_{AM}, I_{BM}, H_1, H_2, H_3$	Yes
[44]	CSC C.	Mid-point C.	SRM	P&O	Commutation angle control algorithm	I_{PV}, V_{PV}	H_1, H_2, H_3	Yes
[45]	SIDO C.	Mid-point C.	SRM	Drift free P&O	Commutation angle control algorithm	I_{PV}, V_{PV}	H_1, H_2, H_3	Yes
[46]	Buck-Boost C.	Mid-point C.	SRM	InC	dwell angle self starting algorithm	I_{PV}, V_{PV}	H_1, H_2, H_3	Yes
[47]	Luo C.	Mid-point C.	SRM	InC	Commutation angle control algorithm	I_{PV}, V_{PV}	H_1, H_2, H_3	Yes

Note: A-MPPT Tracker, B-Motor Driver, C-Motor, D-MPPT Algorithm, E-Control strategy, F-Sensors for MPPT algorithm, G-Sensors for control strategy, Exp-Experimental work, C.-Converter

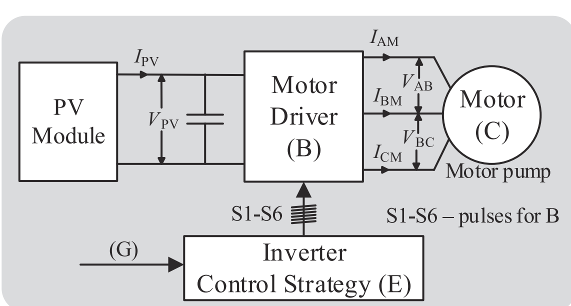

Fig. 4. Block level representation of Single-stage SPWPS.

less noise and a high lifetime of the system. Also, a modified P&O algorithm aided by fast acting ON-OFF supervisory controller is proposed by P. Packiam *et al*. [51] to reduce the power loss due to steady state oscillations of MPPT algorithm. Control strategies used in [48], [50] and [51] are feedforward algorithms, which sense PV voltage and current as disturbances to control the frequency, hence tracking maximum power.

C. Ramulu *et al*. [52] have studied three-level cascaded inverter with MPPT and constant flux control. The proposed system is compared with conventional two-level VSI and is reported to yield better performance.

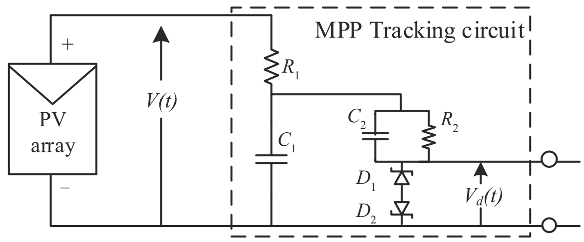

Fig. 5. A Novel six element circuit for MPPT proposed in [53].

M. S. Taha and K. Suresh from Kirloskar Electric Co. Ltd., have implemented the MPPT algorithm embedded with V/F controlled variable frequency drive on commercial IM pump. Authors have reported that the energy utilization is effective from 500 W/m^2 to 1000 W/m^2. Below 500 W/m^2, the MPPT algorithm is disabled to avoid the collapse of DC-link voltage.

A Novel six element circuit shown in Fig. 5 is proposed by C. Dreimeier *et al*. in [53]. The circuit proposed can be embedded into the conventional Variable Frequency Drive (VFD) fed IM system to extract maximum power from the PV source. The circuit produces an analog voltage based on the solar insolation. This analog voltage is fed as a reference frequency signal to the conventional variable frequency drive to match the maximum solar PV power to the load power. The circuit for maximum power tracking is a low-cost proposition to counterfeit the already existing variable frequency drive fed IM pump.

2) Vector Control Algorithms

C. Moulay-Idriss and B. Mohamed [54] have implemented InC method to select an optimal speed for a given insolation and temperature. The speed of the motor is regulated to the optimal speed by employing the DTC algorithm. Authors have concluded that the proposed algorithm results in fast response, no over-shoots, reduced steady-state oscillations and increased system efficiency. However, a small ripple in the water flow is observed due to hysteresis controllers used. An improvisation is provided by C. Moulay-Idriss in [55] with SVM-DTC over conventional-DTC. The proposed SVM-DTC algorithm is claimed to reduce the ripples in water flow observed in [54].

A. Gosh *et al*. [56] have developed a small signal model of the PV fed Inverter assisted IM pump. The small signal model is further used to tune two PI controllers in cascade, one for DC-link voltage control and another for speed control of IM. The P&O algorithm is used to arrive at the reference DC-link voltage for given insolation and temperature. The error in the DC-link voltage is processed to obtain the optimal speed to match the load power and maximum available solar PV power. The error in speed is processed using a vector control algorithm for the inverter. The designed PI controllers are reported to increase the system robustness achieving the desired performance.

S. Shukla and B. Singh have conducted detailed investigations on the reduction of the number of sensors in single-stage IM based pump. In addition to PV voltage and current for MPPT, only DC-link voltage and current are sensed [57]. All other parameters required for control in DTC are derived using sensed DC-link voltage and current. The proposed system is designed and tested for successful working in standalone and battery hybrid mode. Further, exhaustive investigations are conducted on the FOC of IM in [58]−[60]. Speed estimation is proposed using rotor flux and stator flux in [58] and [59] respectively, along with line voltage estimation. Speed, line voltages, and phase currents estimations are proposed in [60]. The reduction in the number of sensors is reported to increase system stability and reduce the cost of the system.

3) Soft Computing Techniques

Off late optimization techniques are seen as advanced algorithms for real-time control of electric drives. The algorithms rely on real-time data and number of datasets used for training and are highly adaptive.

A. Betka and A. Moussi [61] have modeled single-stage IM based SPWPSs as an optimization problem. The objective of optimization is to maximize efficiency (or to minimize nonlinear criterion) by varying frequency and amplitude modulation index of VSI. The proposed algorithm is reported to increase the overall pump efficiency and the amount of water pumped per day.

A. Raju *et al*. [62] have implemented a maximum efficiency algorithm for single stage VSI fed IM PV water pumping system. Maximum efficiency algorithm is formulated as a genetic algorithm problem to generate a reference frequency. It is reported in a study, that for low power applications (less than 600 W), maximum efficiency algorithm yielded better results compared to the MPPT algorithm.

M. M. Elkholy and A. Fathy [63] have presented a Teaching-Learning-Based Optimization (TLBO) algorithm to generate an optimal voltage corresponding to maximum power from the PV source. DC-link voltage regulation is achieved using three level VSI to reduce filtering requirements of the system.

M. Makhlouf *et al*. [64] have formulated the single stage SPWPS as an optimization problem to maximize efficiency of the IM. In addition, the maximum power is extracted from solar PV source using direct vector control algorithm. The combination of maximum power and maximum efficiency algorithm is reported to yield improved overall system efficiency.

B. PMSM Based SPWPS

R. Antenello *et al*. [65] have proposed a single stage PMSM based SPWPS to reduce cost and complexity without compromising on the utilization of available solar energy. Perturbation based extremum seeking controller sets speed reference with a change in solar insolation. VSI with conventional FOC regulates the speed to the desired value for maximum system efficiency. S. Murshid and B. Singh [66] have developed an energy efficient PMSM drive for water pumping with least number of sensors for MPPT and motor control. System variables like speed, position, flux and voltages are estimated

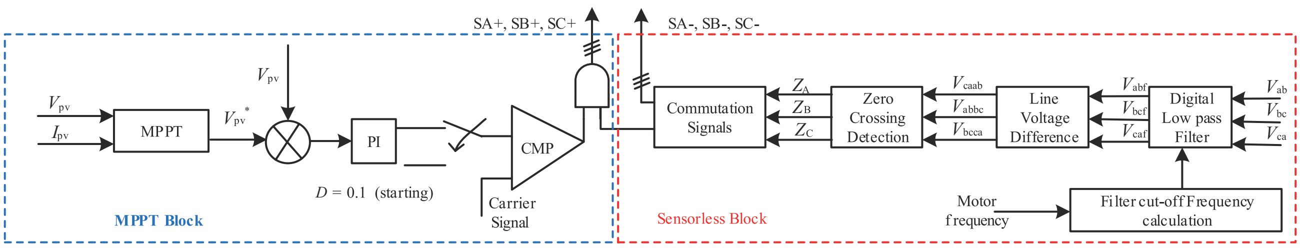

Fig. 6. A novel position sensor-less control algorithm proposed in [68].

using only DC-link voltage for vector control of the motor. Modified P&O algorithm is employed using only DC-link voltage eliminating the use of current sensor.

C. BLDCM Based SPWPS

R. Kumar and B. Singh [67] have presented implementation details of single stage BLDCM based SPWPS. It is reported that the elimination of the boost converter stage in the system has led to reduced cost, complexity, size and improved efficiency.

S. Sashidhar *et al*. [68] have studied that the control using hall-sensors is not reliable for bore-well pump application due to the poor ambiance. Hence the position sensor-less control algorithm shown in Fig. 6 is proposed for BLDCM. The proposed single-stage sensorless WPS results in increased reliability for use in the rural application, with an efficiency of 87% for the BLDC motor and 92% for the VSI at rated power.

D. SyRM Based SPWPS

Synchronous Reluctance Machine (SyRM) offers the degree of freedom in torque production by virtue of its construction. L. Ortombina *et al*. [69] have proposed a simple control strategy for torque regulation in the machine by exploiting an additional degree of freedom. MPPT algorithm is used to generate the reference speed for the machine, and further MTPA algorithm generates current reference by processing the speed error. The torque ripple is considerably reduced, increasing the system efficiency.

A. Varshney and B. Singh have reported the SyRM drive as robust, simple to control and highly efficient for water pumping application [70]. InC algorithm is used to generate the reference speed proportional to available solar insolation. The speed of the machine is further regulated using FOC. The proposed system is said to perform satisfactorily for insolation as low as 0.2 Sun.

M. N. Ibrahim *et al*. [71] have presented a differential evolution algorithm based MPPT for partial shading conditions. The proposed algorithm is reported to yield 52% more flow rate as compared to the conventional P&O algorithm.

E. OEIM Based SPWPS

OEIM is a modified version of IM. It retains all the merits offered by the IM. Also, the OEIM offers other benefits like three level inversion using two-level inverters, reduced motor ripple current due to decoupled PWM, reduced voltage rating of DC-link capacitor and switching devices and increased life of the DC-link capacitor. Several researchers have considered OEIM drive for use in water pumping applications.

A. S. Abdel-Khalik *et al.* [72] have employed two cascaded boost inverter to obtain pure sinusoidal output voltage and ripple free current to drive OEIM pump. The MPPT algorithm is not employed leading to reduced energy utilization. S. Jain *et al*. [73], [74] have presented three level dual inverter equipped with MPPT, V/F and Sampled-Averaged Zero Sequence Elimination (SAZE) algorithms for improved system efficiency. The proposed driver topology provides 3-level output with two 2-level inverters. The SAZE algorithm, in particular, is studied to avoid zero sequence current.

In addition to contributions by [73], [74], a concept of Distributed MPPT (DMPPT) is studied by S. Jain *et al.* [75],[76]. The proposed DMPPT algorithm can be used to extract maximum power from distributed multiple PV sources.

F. SRM Based SPWPS

A. K. Mishra and B. Singh [77] have presented a cost-effective solution for single-stage SRM based WPS. The control strategy is divided into two main parts. Firstly the maximum power extraction using InCalgorithm. The second part is concerning the smooth start of the motor. Both the control strategies are embedded to drive mid-point converter for optimal operation of the entire drive system.

V. B. Koreboina *et al*. [78] have proposed simplified PWM based Modified Lookup Table (MLUT) approach for driving SRM motor and extracting maximum power from solar PV source. The proposed algorithm is reported to offer reduced phase peak, torque ripple and noise of the system.

G. Summary

The research carried out in single stage SPWPS is summarized in Table II The crucial research avenue of single-stage SPWPS is the control strategy because it combines MPPT algorithm and motor control algorithm. The MPPT is formulated to generate the reference frequency (for scalar control) or speed (for vector control) for given insolation using pump affinity laws. In the case of a scalar control algorithm, the frequency is used to generate SPWM or SVPWM pulses

TABLE II
SUMMARY OF SINGLE-STAGE SPWPS

Ref.	Motor Driver (B)	Motor (C)	Control Strategy (E) For MPPT & motor control	Sensors for E (G)	Exp.
[48]	VSI	IM	P&O + Feed forward control for variable frequency operation	I_{PV}, V_{PV}	Yes
[49]	VSI	IM	Hill climbing algorithm + SVPWM pulses to match load and PV power	I_{PV}, V_{PV}	No
[50]	VSI	IM	P&O + SPWM based Volts/hertz Control	I_{PV}, V_{PV}	Yes
[51]	VSI	IM	P&O + Square wave drive, SPWM and SVPWM based Variable Voltage Variable frequency Control	I_{PV}, V_{PV}	Yes
[52]	3-Level VSI	IM	MPPT(Hill-Climbing algorithm) + V/F Control using SPWM	I_{PV}, V_{PV}	Yes
[53]	VSI	IM	A Novel six element circuit + variable frequency control	V_{PV}	Yes
[54]	VSI	IM	InC+ Sensorless DTC	$I_{PV}, V_{PV}, I_{AM}, I_{BM}, V_{AB}, V_{BC}$	Yes
[55]	VSI	IM	InC+ DTC	$I_{PV}, V_{PV}, I_{AM}, I_{BM}, V_{AB}, V_{BC}, N$	Yes
[56]	VSI	IM	P&O with reference voltage perturbation	I_{PV}, V_{PV}	Yes
[57]	VSI	IM	P&O + Sensorless DTC	$I_{PV}, V_{PV}, I_{AM}, I_{BM}$, N	Yes
[58]	VSI	IM	InC + Indirect FOC (Speed estimation using rotor flux + Phase voltages estimation)	$V_{PV}, I_{PV}, V_{DC}, I_{AM}, I_{BM}$	Yes
[59]	VSI	IM	InC + Indirect FOC (Speed estimation using stator flux Phase voltages estimation)	$V_{PV}, I_{PV}, V_{DC}, I_{AM}, I_{BM}$	Yes
[60]	VSI	IM	InC + Indirect FOC (Speed adaptive estimation using generalized integrator approach + Phase voltages estimation + phase current estimation)	$V_{PV}, I_{PV}, V_{DC}, I_{DC}$	Yes
[61]	VSI	IM	Optimization algorithm + feedforward Control	I_{PV}, V_{PV}	No
[62]	VSI	IM	Maximum efficiency + MPPT algorithm	I_{PV}, V_{PV}	No
[63]	VSI	IM	ANN based MPPT + TLBO based motor control	I_{PV}, V_{PV}	No
[64]	MLI	IM	Efficiency optimization + direct vector control	G, T, I_{AM}, I_{BM}, N	No
[65]	VSI	PMSM	Novel MPPT + Conventional FOC	$V_{PV}, I_{PV}, I_{AM}, I_{BM}, V_{AB}, V_{BC}, N$	Yes
[66]	VSI	PMSM	Modified P&O + sensorless FOC	V_{PV}, I_{AM}, I_{BM}	Yes
[67]	VSI	BLDCM	InC+ Electronic commutation algorithm	$I_{PV}, V_{PV}, H_1, H_2, \mathrm{H}_3$	Yes
[68]	VSI	BLDCM	InC+ Sensorless electronic commutation algorithm	I_{PV}, V_{PV}	Yes
[69]	VSI	SyRM	Novel MPPT + SVM based MTPA algorithm	$I_{PV}, V_{PV}, I_{AM}, I_{BM}, N$	No
[70]	VSI	SyRM	InC+ FOC	$I_{PV}, V_{PV}, I_{AM}, I_{BM}, N$	Yes
[71]	VSI	SyRM	Differential Evolution based MPPT algorithm + FOC	$I_{PV}, V_{PV}, I_{AM}, I_{BM}, N$	Yes
[72]	Boost inverter	OEIM	V/F Control	–	No
[73]	Dual two-level inverter	OEIM	Hill-Climbing algorithm +V/F Control	I_{PV}, V_{PV}	Yes
[74]	Dual three-level inverter	OEIM	Hill-Climbing algorithm +SAZE PWM + V/F Control	I_{PV}, V_{PV}	Yes
[75]	Two VSI's	OEIM	Dual MPPT(Hill-Climbing algorithm) +V/F Control and Decoupled PWM algorithm	V_{PV1} & I_{PV1} V_{PV2} & I_{PV2}	No
[76]	Two VSI's	OEIM	Dual MPPT + 'Unified voltage' carrier based SVPWM algorithm	V_{PV1} & I_{PV1} V_{PV2} & I_{PV2}	Yes
[78]	Mid-point Converter	SRM	MLUT based MPPT + Simplified PWM algorithm	V_{PV}, N	Yes

Note: B-Motor Driver, C-Motor, E-Control strategy, G-Sensors for control strategy, Exp.-Experimental work

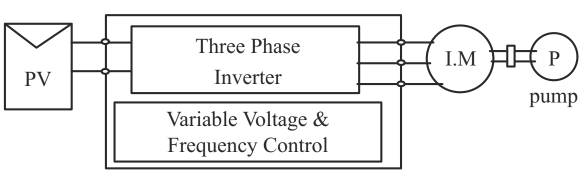

Fig. 7. Block level implementation details of VFD (single stage SPVWPS) [79].

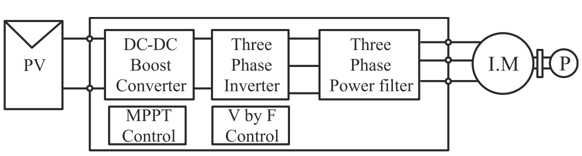

Fig. 8. Block level implementation details of SPCM (Two stage SPVWPS) [79].

for VSI to extract maximum power from the solar PV source and drive the motor pump simultaneously. In vector control algorithm, the reference speed generated is used to implement sensored or sensorless algorithms to drive the VSI fed motor pump while extracting maximum power from the source. The discussions for the choice of motor, sensors and motor driver are same as discussions presented for multi-stage SPWPS in section III-F.

V. MULTI-STAGE VERSUS SINGLE-STAGE SPWPS

This section presents the results of experimental investigations conducted by few researchers describing the comparison of multi-stage versus single-stage WPS.

K. Yadav *et al*. [79] have considered two systems, Variable frequency drive (a single stage SPWPS) and Sine-wave Pump Controller with MPPT (SPCM, a two-stage SPWPS) shown in Fig. 7 and 8 respectively. VFD considered for study is not reported to have any algorithm for tracking maximum power from PV source. On the contrary, perturbation based MPPT algorithm is employed for two stage SPCM controller. Study is conducted to evaluate the performance of both systems at three different heads. It is observed that at lower head the difference in efficiency is less. However, with higher head two stage SPCM is found to be more efficient compared to its single stage counterpart. Results of investigation conducted in [79] are motivating enough to take up research to improve wire to water efficiency of single stage SPVWPs

R. Kumar and B. Singh have conducted a similar study on BLDCM based SPWPS [67]. A simple control strategy for single-stage BLDCM based WPS is proposed capable of extracting maximum power from the solar PV source. In comparison with [32] (Fig. 9) and [36] (Fig. 10), the DC-DC converter is eliminated in [67] (Fig. 11); Also, the number of sensors for MPPT and motor control, DC-link capacitor value, system size and the overall cost is reduced while an increase in system efficiency is reported. The authors have concluded that the proposed system (Fig. 11) outperforms conventional systems(Fig. 9 and 10) interms of cost, size, efficiency and complexity.

S. Sashidhar *et al*. [68] have presented an exhaustive compo-

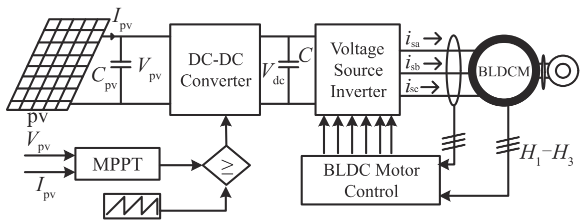

Fig. 9. Two-stage BLDCM based SPWPS with position and phase current sensing [32].

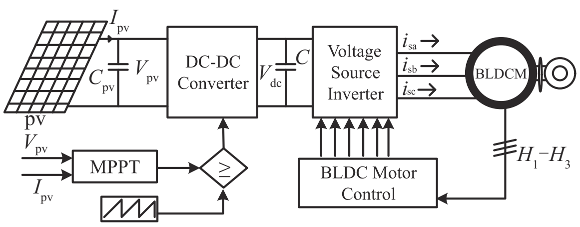

Fig. 10. Two-stage BLDCM based SPWPS with position sensing only [36].

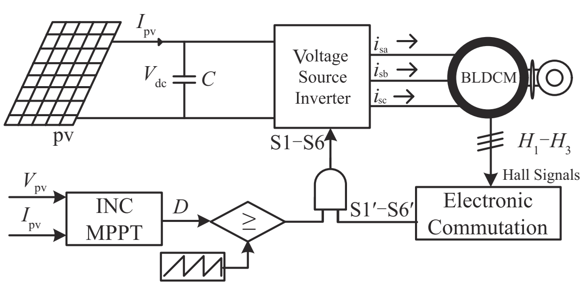

Fig. 11. Proposed Single-Stage BLDCM based SPWPS with position sensing only [67].

nent level comparison of single-stage BLDCM based SPWPS and conventional two-stage IM based SPWPS. Though a 2 HP BLDCM pump ($396) is expensive compared to 2 HP IM pump ($286), the solar panel required to pump the same quantity of water is 1290 W and 2500 W, respectively. Thus the cost of the proposed single-stage SPVWPS (BLDCM pump based system) is lesser compared to conventional two-stage SPVWPS (IM pump based system). In addition the BLDCM based system is expected to yield improved efficiency due to reduced system components (elimination of DC-DC converter stage) and improved motor efficiency.

S. Jain *et al*. have presented a comparison of three systems, IM based multi-stage SPWPS [15], IM based single-stage SPWPS [48] and the proposed OEIM based single-stage SPWPS [73]. The proposed system consists of 1-stage 3-level VSI reducing the DC-link capacitor value, size and cost considerably hence reducing the overall system cost. The authors conclude that the proposed OEIM based WPS is a simple, cost-effective and efficient system due to the reduction of DC-link capacitor value, number of sensors used for system control and elimination of DC-DC converter stage.

Investigations on comparisons between single-stage SPWPS and multi-stage SPWPS using IM, BLDCM and OEIM are presented in this section and findings of the research are summarized in Table III.

VI. Wind WPS

Small aerogenerators with blade diameter of 3–5.5 meters are used for low power application like WPS. The performance of generators like Self Excited Induction Generator (SEIG) and Permanent Magnet Synchronous Generators (PMSG) for different motors and power electronics interface are reviewed in this section.

A. Shaltout and M. Abdel-Halim [80] have analysed stand-alone induction generator directly feeding an IM without intermediate DC-link. Maximum power extraction is demonstrated by adjusting the exciting current using static VAR compensator. M. S. Miranda *et al*. [81] have studied IM based pump fed by wind-driven SEIG. PWM converter (VSI) with vector control is employed to control active and reactive power flow to the load while maintaining the terminal voltage constant. T. Ouchbel *et al*. [82] have proposed an MPPT algorithm for wind-driven SEIG fed IM pump. A thyristor-based Static Voltage Compensator (SVC) is used to optimize the quantity of the pumped water. Also, a comparison of wind power utilized with and without MPPT algorithm is presented showing better energy utilization with the proposed MPPT algorithm.

A single phase IM pump fed by wind-driven PMSG is studied by D. Lara *et al*. in [83]. Operating efficiency of 70% to 95% is reported with proposed MPPT based V/F algorithm.

Three MPPT algorithms namely P&O, InC and FLC are evaluated for wind-driven SEIG fed PMDC motor pump [84]. FLC is evidenced to give better results compared to conventional P&O and InC algorithms.

M. A. Zeddini *et al*. [85] have presented Particle Swarm Optimization (PSO) for a standalone, variable speed, wind-driven SEIG feeding IM pump with maximum power tracking. The proposed algorithm uses only power input and does not require knowledge of wind speed, air density, and turbine parameters to extract maximum power.

The details of the research in wind WPS is summarized in Table IV. In the wind WPSs, the choice of the generator and the motor pump decides the power electronic interface and hence the control strategy. It is evident from Table IV that the SEIG (power generation) and the IM (for water pumping) are the popular choices owing to the reduced cost, low maintenance and rugged construction. The power electronic interfaces include thyristor-based circuits (SVC, TCR and inverter) and VSI to control the active and reactive power at the PCC. It is observed that MPPT algorithms are popular in Wind WPSs in view of increasing the system efficiency.

VII. Hybrid Wind-PV WPS

Renewable energy is very often seen as a clean and attractive choice for powering standalone applications to remote

TABLE III
SUMMARY OF COMPARISONS BETWEEN SINGLE-STAGE AND MULTI-STAGE SPWPS

Ref.	Systems Under Comparison	Remarks
[79]	Single-stage VFD Fig. 7 & Sine wave pump controller with MPPT Fig. 8	· It is concluded that SPCM is said to have better efficiency · Comparison would have been apt, if both systems were with MPPT
[67]	Two-stage BLDCM based SPWMS with position and current sensing(Fig. 9) Two-stage BLDCM based SPWMS with position sensing only (Fig. 10) Single-stage BLDCM based SPWMS with position sensing only (Fig. 11)	· A detailed comparison is presented on three systems based on cost, compactness, efficiency, complexity and DC bus capacitance · Single-stage WPS is reported to be superior to existing two systems
[68]	Conventional two-stage submersible IM based SPWPS Single-stage BLDCM based SPWPS	· Sensorless speed control strategy for single-stage system with mppt is employed · In single-stage system motor capacity to pump the same amount of water is reduced. · Overall cost of single-stage system is less than conbentional two-stage system
[73]	Multi-stage, IM based SPWPS [15] Single-stage, IM based SPWPS [48] Single-stage, OEIM based SPWPS (proposed) [73]	· The overall cost of the proposed system is reported to be least owing to reduced voltage rating of capacitor and switches used Three level voltage output results in in reduced filtering requirements and reduced torque ripple

TABLE IV
SUMMARY OF WIND WPS

Ref.	Generator	Motor	PE.	Control Strategy	Exp.
[80]	SEIG	IM	SVC	MPPT algorithm	Yes
[81]	SEIG	IM	VSI	Vector Control	Yes
[82]	SEIG	IM	SVC	MPPT algorithm	Yes
[83]	PMSG	SPIM	SVC	MPPT algorithms	Yes
[84]	PMSG	PMDC	Rectifier and Boost-Converter	MPPT algorithms: P&O, InC & FLC	No
[85]	SEIG	IM	TCR	MPPT using PSO	Yes

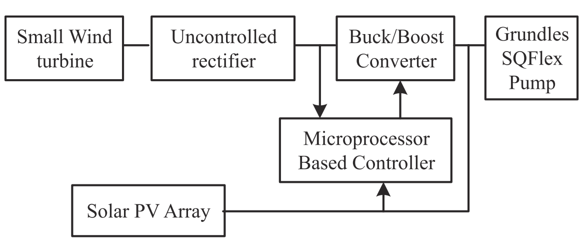

Fig. 12. Block diagram of hybrid Wind-PV system for DC motor pump [88].

locations which are isolated from the grid or at places where transmission of power is uneconomical. However solar or wind energy alone cannot be relied upon due to seasonal and daylight variations. Owing to complimentary profile, hybrid Wind-PV systems for standalone applications can be seen as a reliable and feasible alternative to wind-diesel and battery coupled solar systems [86]. In this section, the review of hybrid Wind-PV based water pumping system is presented. Several researchers have investigated hybrid Wind-PV systems for standalone applications considering generic load (R/RL/non-linear loads). However, with little or no change in control strategy, the motor pump can be used in place of the generic load to study water pumping application. Hence, a few selected standalone hybrid Wind-PV systems are also discussed which can be easily adopted for water pumping.

Intermittent nature of solar or wind energy alone prevents

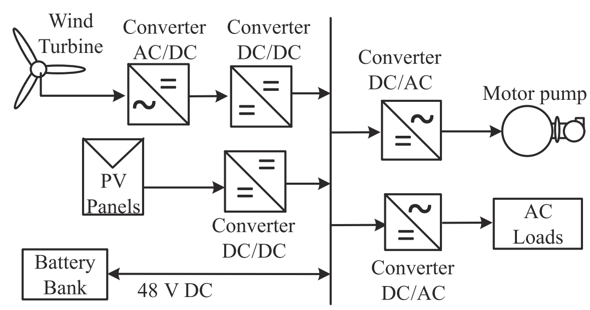

Fig. 13. Block diagram of renewable energy hybrid power system (RE-HPS) for agricultural applications [89].

the system from being sufficiently reliable for standalone applications. Hence, pumped hydro storage for the hybrid Wind-PV system is studied in [87]. Authors have carried out several simulation case studies on data available locally, and it is concluded in their study that the combination of hybrid Wind-PV with pumped hydro storage attains 100 % energy autonomy for standalone applications.

B. D. Vick and B. A. Neal [88] have presented an analysis of the following systems: i) Solar PV water pumping system, ii) Wind-driven water pumping system and iii) Combined hybrid Wind-PV water pumping system for the same location. The topology configured for the hybrid Wind-PV WPS is shown in the Fig. 12. The performance of the hybrid system is reported to be superior to solar PV or wind energy system alone, subject to geographical location of the site. Also, it is indicated in the study that the configuration of the hybrid Wind-PV system is more challenging in standalone mode compared to the grid-connected system due to varying system voltage.

A. K. Traoré *et al*. [89] have conducted investigations on Renewable Energy Hybrid Power System (RE-HPS) for agricultural applications shown in Fig. 13. The authors have investigated three algorithms for energy management amidst renewable energy sources (SPV and wind energy), water pump, battery storage, and other small farm equipment. It is

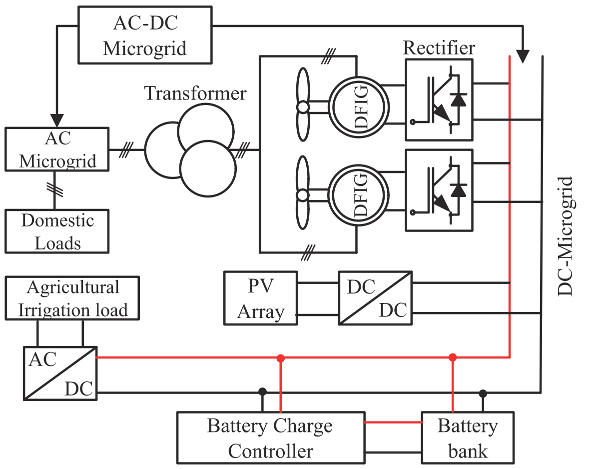

Fig. 14. Hybrid Wind-PV based AC and DC micro-grid implementation [90].

shown in the results of the simulation that the third algorithm (which prioritizes the battery charging over water pumping and feeding other loads) fetches the most significant system efficiency.

A. Parida and D. Chatterjee [90],[91] have implemented Hybrid Wind-PV based AC and DC micro-grid with automatic power exchange between AC and DC microgrid. The system consists of two wind turbines, PV system, and battery storage feeding agricultural pumps and domestic loads as shown in Fig. 14. The battery storage requirements are reduced due to the corresponding profile of wind energy profile and solar PV source.

S. Rehman and A. Z. Sahin studied optimal sizing of hybrid Wind-PV system using Homer software in regions like Dhahran, Riyadh, Jeddah, Guriat and Nejran [92]. Near optimal sizing of hybrid Wind-PV system is reported to give constant pumped output throughout the year. However, over pumping is observed in spring and summer due to high sunlight and long days.

M. Rezkallah *et al*. [93] have attempted to integrate distributed energy sources (solar PV and wind energy) at the DC bus. Two boost converters, dump load, battery charging/discharging circuit and dedicated inverter perform the power conditioning of the proposed system. Three control strategies are implemented for the stable and efficient operation of the system. The first two algorithms extract maximum power from the solar PV source and wind turbine. The third algorithm regulates the AC output voltage against changing weather conditions. The system under consideration is tested against sudden changes in load (non-linear and unbalanced load).

As compared to the system configuration in [93], a machine side Voltage Source Converter (VSC) in place of the boost converter is proposed in [94] by S. Pradhan *et al*. A composite sliding mode controller for machine side VSC for the hybrid Wind-PV system with battery energy storage is implemented for rural electrification.

S. Malla and C. Bhende [95] have presented a hybrid energy system comprising wind and solar PV source. The battery system, fuel cell, and dump load are connected in parallel at the DC bus to store surplus power. The PWM VSI is connected between DC bus and AC load. Simple control strategies for extracting maximum power and regulating DC-link voltage are discussed in detail.

S. A. Daniel and N. Ammasai Gounden [86] have presented a novel method of integration between solar PV and wind energy with minimal power electronics interface. The square wave inverter is used to integrate renewable energy sources. Successful operation of the proposed system is demonstrated against variations in irradiance and wind speed. Since only one converter is used for integration, DC-link voltage regulation and maximum power extraction are not addressed using this topology.

M. Arutchelvi and S. A. Daniel further proposed an improvisation to [86] in [96] by including boost converter for DC-link voltage regulation. A constant DC-link voltage is achieved for changing solar irradiance and wind regimes. Further, an effort is made to extract maximum power using the buck-boost converter and to regulate DC-link voltage in [97]. The buck-boost converter is designed to extract maximum power from the solar PV source when the battery is sourcing PWM-VSI and smoothly transfers control back to voltage regulation mode in the absence of the battery.

S. L. Prakash *et al*. [98] have investigated a hybrid Wind-PV system feeding the non-linear and unbalanced load. A simple control strategy is presented to regulate the DC-link voltage against variations in load, solar irradiance and wind speed. Also, the battery-less operation of the system is demonstrated with extensive field tests.

The hybrid Wind-PV system is the emerging field of the renewable energy system. Numerous researchers have consolidated and published their findings in the area of standalone hybrid Wind-PV systems concerning different power electronics topologies, wind generators and control strategies [99]–[101]. A new standalone hybrid Wind-PV system can be adapted for application in water pumping with appropriate changes based on the motor pump and wind generator chosen.

The complexity increases in hybrid Wind-PV system due to the presence of multiple sources. The power electronic interface and related control strategies are chosen based on the type of the wind generator, type of the motor pump and the PCC between the sources and the load. The details of the implementation of the research discussed in this section are summarized in Table V.

VIII. Discussions and Future Scope

In this section, an attempt is made to give pointers for readers to pursue future work in REWPS. The IM has been a popular choice for pumping water due to its robustness, simplicity in construction, control and maintenance cost. However, other machines like permanent magnet motors (BLDCM, PMSM) and special machines (SyRM, SRM) are also fast emerging due to factors like increased efficiency, power density, ruggedness

TABLE V
SUMMARY OF HYBRID WIND-PV WPS

Ref.	Wind Generator	Load	Load Control	Power Electronic Interface Wind Generator	Solar PV source	Load Control	Control Strategy Wind Generator	Solar PV source	Exp.
[86]	SEIG	Resistive load		Voltage Source Inverter		Conventional Square wave drive			Yes
[87]	Not Specified	Centrifugal pump		DC-AC Inverter		Not Specified			Yes
[88]	AC generator	Grundfos SQFlex Pump	Buck-Boost Converter	Rectifier	Buck-Boost Converter	Energy management strategy			Yes
[89]	AC generator	motorpump & AC loads	VSI	Rectifier + DC-DC Converter	DC-DC Converter	3 Power management strategies			No
[93]	BLDCM	Balanced & unbalanced	VSI	Rectifier + Boost-Converter 1	Boost Converter 2	VSI control	MPPT algorithm	MPPT InC algorithm	Yes
[94]	PMSG	Linear & Non-linear	VSI 1	VSI 2	Boost Converter	VSI 1 Control	MPPT (wind)	MPPT (P & O)	Yes
[95]	PMSG	loads	VSI	Rectifier + Boost-Converter	----	VSI Control	MPPT (wind)	----	No
[96]	SEIG	RL load	VSI	VSI	Boost Converter	VSI Control	VSI Control	MPPT (P & O) & Voltage Control	Yes
[97]	SEIG	RL load	VSI	VSI	Buck-Boost Converter	VSI Control	VSI Control	MPPT (P & O) & Voltage Control	Yes
[98]	SEIG	RL load & Unbalanced Load	VSI	VSI	Boost Converter	VSI Control	VSI Control	Sliding Mode Voltage Control	Yes

and reduced cost. Based on the literature reviewed in this paper, the following topics are identified as niche areas for future research.

A. Multi-Stage SPWPS

- High-gain DC-DC converter with high efficiency and wide range for MPPT tracking is desired to effectively utilize available solar PV power with required power quality indices.
- High gain multi-input DC-DC converter can be studied to integrate solar PV source with other renewable energy source like wind energy to effectively harness power from these non-linear sources with amenable operating voltages and currents.
- Research on current source inverters for water pumping application can be taken up as GAN and SiC devices are fast emerging in the field of power electronics [102], [103].
- Performance analysis of commercially available IE4, IE3 and IE2 induction machines has to be studied in water pumping applications with focus on their impact on efficiency and overall cost of the system.
- Most of the algorithms reported in the study are perturbation based algorithms leading to steady state oscillations resulting in reduced energy utilization. Soft computing techniques like FLC with minimal or zero oscillations for real-time insolations can be studied. Also, algorithms with only one sensor without compromising on energy utilization of solar PV source are in demand.
- Vector control algorithms evidently have an edge over scalar control algorithms in terms of performance, however they suffer adaptability to different commercial motors as the controller tuning requires knowledge of machine parameters. Vector controllers can be designed with adaptive intelligence for self tuning for commercial use.
- Control strategy mainly consists of the MPPT algorithm and motor control algorithm. The number of sensors used for motor control is seen to be reducing over a decade. The continuous progress in the microcontroller/DSP technology has led to easy development of system variable estimation based algorithms enabling sensorless control at affordable prices.

B. Single-Stage SPWPS

- Control algorithms to effectively transfer solar PV power at low irradiances are to be studied.
- Most of the soft computing algorithms for single-stage SPWPS evidenced, are limited only to a simulation study. There is a need for low-cost hardware implementation of these algorithms for better performance.

C. Hybrid Wind-PV WPS

- The water pumping using hybrid Wind-PV system is restricted to PMDC and IM pumps only. Other motors and appropriate topology suitable for water pumping should be explored and compared for system efficiency and energy utilization of sources.

- Exact source to load matching at all times in hybrid Wind-PV based WPS is difficult due to multiple sources and their stochastic nature. Hence, a power electronic interface feeding power from renewable sources to load and facilitating interface to divert the surplus power to the grid can be investigated.
- Comparisons can be made between PV assisted wind-based WPS (Wind energy is prominent), and wind assisted PV based WPS (Solar PV energy is prominent) specific to site conditions for better efficiency of the overall system.

D. Grid Connected SPWPS

The grid-connected WPSs and SPWPSs are not reliable due to consistent power cuts (in rural India) and continuously varying insolation respectively. As a step towards a reliable solution and to facilitate uninterrupted water pumping, several researchers have interfaced grid with SPWPS. The published research is presented in this section as a pointer to the reader to pursue research in grid-connected SPWPSs.

- Grid interfaced SPWPS: U. Sharma *et al*. [104] have interfaced two-stage IM based SPWPS with the grid to facilitate uninterrupted water supply. A similar study is conducted by R. Kumar and B. Singh [105] using BLDCM pump.
- Grid interactive SPWMS: B. Singh and S. Murshid [106] have proposed PMSM based grid-interactive SPWPS which facilitate uninterrupted water supply and transfer of surplus power to the grid. Similar studies are carried out by R. Kumar, B. Singh [107] and S. Shukla, B. Singh [108] on BLDCM pump and IM pump respectively.

E. Techno-Economic Analysis

Performance and economic evaluation of REWPS is gaining importance due to high initial investment. Several investigations carried out in assessing techno-economic viability of the installed REWPS are presented in this section.

- SPWPS: K. Stokes *et al*. [109] have investigated 251 sites in western US to report findings concerning system cost, reliability and the system performance. Metrics like Initial Capital Cost (ICC), LCC and revenue are studied by P. E. Campana [110], indirect benefits like reduction of GHG gases and carbon footprint are also discussed. C. Zhang *et al*. [111] conducted economic assessment of SPWPS for 20 chinese dairy milk production and agricultural fields. Metrics like annual discounted cost, revenue, and net profit for each of 20 cases are studied to report economic crop savings and reduced carbon footprint. Diesel powered water pumping is studied in comparison with SPWPS by M. Mahmoud *et al*. [112] and L. Odeh *et al*. [113]. In both the studies, reliability and economic feasibility of SPWPS is evaluated to be superior compared to diesel powered water pumping. Effective utilization of the installed SPV panels in SPWPS with MPPT and direct coupling is presented by A. Allouhi *et al*. [114].
- Wind WPS: P. T. Smulders *et al*. have illustrated a simple procedure to calculate the investment costs per average Watt hydraulic power output considering wind energy and solar energy [115], [116]. T. Ayodele *et al*. [117] have presented technical, economical and environmental merits of water pumping using wind energy for Oyo state of Nigeria. Over 16 years of wind data in the region is assessed to present the the annualized LCC and cost per cubic meter of water pumped.
- Hybrid Wind-PV WPS: N. Khattab *et al*. [118] have illustrated detailed techno-economic analysis on Net Present Cost (NPC) and Cost Of Electricity (COE) of WPS using PV, Hybrid Wind-PV and diesel generator employing PVsyst software. S. Rehman *et al*. [92] have investigated Hybrid Wind-PV systems using Homer tool and reported that the hybrid Wind-PV WPS results in optimal monthly water pumping in Dhahran, Riyadh, Jeddah, Guriat and Nejran of Saudi Arabia.

TABLE VI
BRIEF COMPARISON OF DIFFERENT WPSS

Parameter	A	B	C	D
Load matching	Easy	Easy	Difficult	Easy
Reliability	Medium	Low	High	High
Power Converters	2 or more	1	2 or more	2 or more
Control Strategy	Simple	Complex	Complex	Complex
DC-link capacitor	2	1	2 or more	2 or more
Cost	Medium	Low	High	Medium
Efficiency	Low	High	Medium	Medium

A: Multi-stage SPWPS, B: Single-stage SPWPs, C: Hybrid Wind-PV WPS and D:Grid connected SPWPS

F. REWPS: Merits, Demerits and Application

The factors affecting the efficiency of the REWPS is discussed at length in this paper from electrical engineering perspective. This section is an attempt to consolidate the learnings of the literature studied for different REWPSs. A brief comparison of different REWPSs along with merits, demerits and possible application is also discussed.

Table VI presents the comparison of different REWPSs concerning few parameters of interest to improve system efficiency.

- Multi-stage SPWPS: Most commonly found REWPSs with stable DC-link voltage and good performance under low solar insolations. The system utilizes two converters to feed the solar PV power to the load, hence increasing the losses, cost and reducing the system efficiency when compared to single stage SPWPS. Such systems are abundantly employed for irrigation in developing countries like India using IM pump.
- Single-stage SPWPS: The system employs single power converter to feed the load from solar PV source, hence increasing the system efficiency at the reduced cost. These systems suffer DC-link voltage stabilization problems at

low solar insolations. Single-stage systems are popular for permanent magnet motors which can operate efficiently at low DC-link voltage without compromising on system efficiency and reliability.

- Hybrid Wind-PV WPS: The system involves two non-linear renewable energy sources whose availability is complimentary in nature. Source to load matching is difficult and eventually the cumulative hybrid power capacity always exceeds the load capacity. Due to the complimentary nature of the sources, these systems are used in isolated areas where the continuous water/power supply is desired (community drinking water supply, irrigation, household applications and other agricultural applications) subject to favorable weather conditions.
- Grid connected SPWPS: Conventional SPWPS connected to grid with bi-directional power flow is the most reliable solution for water pumping. The water requirement is fulfilled by grid in absence of solar insolation and the surplus power generated if any is fed to the grid. Such systems need additional converters and PLL algorithm for grid interfacing. Also, the quality of the power generated has to meet certain power quality indices. Irrigation fields with grid connectivity opt for grid-connected SPWPS to sell the surplus power to the grid.

IX. Conclusions

This paper has attempted to consolidate the research in renewable energy-based water pumping systems. Exhaustive research with the primary focus in the field of electrical engineering like power electronics interface, the motor used for pumping and mainly the control strategy employed for the effective energy utilization of the renewables is presented. The following are the conclusions of this work:

- Investigations conducted on multi-stage SPWPSs, single-stage SPWPSs, Wind WPSs and hybrid Wind-PV systems have been reviewed in detail.
- In each of the systems mentioned above, various research avenues have been conferred to the reader namely, the power electronics interface, MPPT algorithms, type of the motor, motor control algorithms and sensors used for the algorithms.
- Findings of several investigations conducted to compare the performance of multi-stage WPS with single-stage WPS have been presented to weigh the performance of the WPSs.
- Niche areas in REWPSs have been indicated to readers to pursue future research.

This review paper is an effort to guide researchers consolidating work in the area of the REWPS with an emphasis on aspects of electrical engineering (type of motor, power electronics interface and control strategies). In a country like India, which suffers irregular monsoons, harnessing renewable energy sources efficiently to fulfill the requirement of water will be the dire need of the near future. Also, the geographical location of the nation is favorable to produce energy from renewable sources like sunlight and wind. Hence, the authors are in the developmental work of control strategies for REWPSs.

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