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Article

Intelligent Control for SEPIC-Fed BLDC Solar PV Water Pumping Systems with Enhanced Energy Efficiency

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Abstract: One of the most common and commonly used decentralized uses of renewable energy is solar photovoltaic (PV) water pumping, which provides an alternative to diesel-powered irrigation and drinking-water provision in remote and off-grid areas. Of all the different combinations of motor and converter reported in the literature, the brushless direct current (BLDC) motor driven by single-ended primary inductor converter (SEPIC) has proven to be a particularly appealing design since it offers the high efficiency and low maintenance of BLDC machines with either the wide-range buck-boost capability, constant input current, and non-inverting output of the SEPIC topology. This is a review of the state of the art of intelligent control strategies implemented on SEPIC-fed BLDC solar PV water pumping systems, especially maximum power point tracking (MPPT), sensorless commutation, and adaptive speed/torque control. The traditional approaches that include Perturb and Observe and Incremental Conductance are discussed as well as intelligent approaches that include fuzzy logic control, artificial neural networks, adaptive neuro-fuzzy inference systems (ANFIS) and bio-inspired metaheuristic optimization methods which include particle swarm optimization, genetic algorithms and grey wolf optimization. The review also addresses system-level integration, converter design issues, energy efficiency improvement mechanisms and relative performance in terms of tracking performance, steady-state ripple, partial shading resistance and complexity of implementation. Potential research issues associated with computational load, sensor reliance, standardization and techno-economic feasibility are pinpointed and future research opportunities with regard to hybrid intelligent controllers, digital twins, and Internet-of-Things (IoT)-enabled predictive control are described. The review aims to be a summary of research that can be used by researchers and practitioners in the development of next-generation, high-efficiency solar water pumping systems.

Keywords: - Solar PV Water Pumping, BLDC Motor, SEPIC Converter, MPPT, Sensorless Control, Fuzzy Logic/ANFIS, Bio-inspired Optimization

1. Introduction

The availability of clean water supply to irrigate and drink is a major issue in most rural and remote areas where there is no or less reliable grid power. Historically dominant, diesel-based pumping systems are linked to considerable recurring fuel expenses, greenhouse gas emissions, and maintenance overheads and are becoming less appealing in the light of global decarbonization goals. A solar photovoltaic (PV) water pumping systems (SPWPS) has therefore received a lot of momentum as a clean, low-maintenance, and cost-effective alternative especially in areas with high solar irradiation.

A standard SPWPS consists of a PV array, power-conditioning stage, a motor drive, and a pump, which is mechanically coupled to the motor shaft. The effectiveness of the power-electronic interface and the properties of the electric motor used determine the performance of the entire system. The most popular types of pump drives in the past were induction motors (IM) and permanent magnet DC (PMDC) motors, but these types have drawbacks: induction motors have to have extra starting and control circuitry and are less efficient at lower loads, and PMDC motors have to wear brushes, create arcs and require maintenance, which is not very desirable in remote rural applications.

The brushless direct current (BLDC) motor has become an increasingly popular option due to its ability to maintain the desirable torque-speed properties and ease of control of a DC machine, and avoid the mechanical commutator and brushes by using electronic commutation. This provides greater efficiency, greater power density, lower acoustic and electrical noise and significantly lower maintenance demands - all qualities that are very desirable in unattended and off-grid pumping systems. To achieve the maximum efficiency of the BLDC-driven pump, however, the motor needs to be fed with regulated DC-link voltage which follows the maximum power point (MPP) of the PV array over the entire range of irradiance and temperature change, and at the same time the switching losses and current ripple must be kept to a minimum.

With a host of DC-DC converter topologies suggested in the literature on PV interfacing, the single-ended primary inductor converter (SEPIC) is one topology that is particularly suitable to this application. SEPIC has continuous step-up/step-down conversion, unlike the buck or boost converters that only provide unidirectional conversion, and the non-inverted polarity of the output of the conventional inverter-fed BLDC drives. Moreover, the sustained input-current nature eliminates ripple at the PV terminals thus enhancing MPPT accuracy and minimizing the loss of power due to partial shading. The above features render the SEPIC-fed BLDC configuration a widely used design in recently published solar water pumping systems.

Enhanced energy efficiency in such systems, however, cannot be just a converter-design issue, but a concerted control approach involving MPPT at the PV interface, duty-cycle regulation at the SEPIC stage, and speed/torque regulation at the BLDC drive. Traditional control methods like Perturb and Observe (P&O) and Incremental Conductance (INC) MPPT, along with proportional-integral (PI) speed control, are computationally straightforward, but have reported weaknesses such as steady-state oscillation about the MPP, slow response to rapidly changing irradiance, and are prone to convergence in local maxima in the presence of partial shading. Such constraints have stimulated a large amount of research in intelligent control methods, such as fuzzy logic control (FLC), artificial neural networks (ANN), adaptive neuro-fuzzy inference systems (ANFIS), and bio-inspired metaheuristic optimization algorithms, which are faster, less steady-state ripple, and more resilient to environmental and load disturbances.

This article is a review of the intelligent control strategies of SEPIC-fed BLDC solar PV water pumping systems aiming to be both an introduction to the topic to researchers new to the field, and a unified reference for those looking to gain a comparative insight into the existing techniques. The rest of the paper is structured to the following. Section 2 gives a summary of water pumping system architectures of solar PV. In section 3, the SEPIC converter topology is discussed and its design considerations addressed. Section 4 will discuss the basics of BLDC motors and drive plans. Section 5 reviews traditional and smart MPPT methods. Section 6 looks into the intelligent control architectures. Section 7 talks about system level integration. In section 8, a comparative analysis is provided. Section 9 talks about mechanisms of energy-saving. Section 10 and 11 provide identification of the challenges and future research directions and Section 12 brings to the end of the paper.

2. Solar PV Water Pumps Overview.

2.1 System Configurations

The solar PV water pumping systems can be categorized into two broad categories based on two factors: the availability of energy storage or lack thereof, and the kind of motor used. Configuration based on storage includes a battery bank to smooth out the intermittency of the solar generation and allow the pumping to continue without regard to the instantaneous irradiance but batteries increase the cost of capital, maintenance load and round trip power losses. Direct-coupled (battery-less) systems, in contrast, drive the pump directly off the PV array with a power-conditioning stage, without electrical storage to absorb supplydemand imbalances, instead using water storage tanks to do so. Direct-coupled is typically desired due to its cheaper cost, increased reliability and reduced maintenance, as long as the control system can adjust the operating point of the pump in real-time to the available solar power a feature that puts considerable stress on the MPPT and the motor-control policy.

In the power-conditioning phase, the PV array is often connected to the motor drive via a DC-DC converter which does MPPT, then an inverter (to AC or brushless DC motors) or direct DC-link connection (to brushed DC motors). These options of converter topology, switching frequency and control algorithm all of which determine the ratio of the theoretically achievable solar energy that is actually exploited as useful hydraulic output.

2.2 PV Pumping Motors.

One design choice in SPWPS is the choice of the electric motor. Induction motors are inexpensive and rugged, but need a three-phase inverter, and do not operate with high efficiency at light load - a condition that is often experienced during the morning and evening hours of low irradiance. PMDC motors are easy to control and have good starting torque but are restricted by wear of the brushes and commutators but this is problematic in unattended installations, which can run years without service. Switched reluctance motors (SRM) have the advantage of ruggedness and lacking permanent magnets, but with the disadvantage of torque ripple and acoustic noise. The BLDC motor integrates much of the above: it is as efficient and offers as high a torque density as permanent-magnet machines, with the elimination of brush-related maintenance due to electronic commutation and favourable power to weight ratio, which leads to the size and cost of the mechanical pump assembly being smaller and less expensive. These features have seen BLDC motors becoming more popular in commercial solar pumping equipment, especially submersible and surface-mount centrifugal pumps in the sub-5 kW scale of typically sub-irrigated smallholder irrigation and community water supply.

2.3 PV Array and System Sizing PV.

It is critical to have the PV array sized correctly in relation to the rated hydraulic power of the pump to be able to have satisfactory system performance over the entire range of seasonal variation of irradiance. Small arrays lead to inadequate flow at times of maximum water demand, whereas oversized arrays are more expensive to install than the amount of benefit they offer, as the surplus power beyond the nominal capacity of the pump cannot be effectively utilized unless it is absorbed by supplementary loads or storage. Sizing of the array is generally determined by a combination of the profile of the daily solar insolation at the site, the total dynamic head (static lift and friction losses) the pump will have to be able to overcome and the desired daily water-volume goal, and is usually represented by simplified sizing charts or more complex hourly simulation models. This sizing exercise is interacted with the intelligent MPPT and motor-control strategy: The larger a controller capable of harvesting a larger fraction of the theoretically available PV energy in varying irradiance, the smaller is the size of a PV array needed to achieve a given water-yield target, and the practical economic relevance of the control-strategy options discussed in this paper.

Selection of pump is also dependent on the electrical design. Although the torque-speed characteristic of centrifugal pumps is approximately quadratic, centrifugal pumps are well suited to variable-speed BLDC drives due to the ability to operate efficiently over a wide range of speed without the need to operate at a fixed point, unlike positive-displacement pumps, which provide a more constant load on torque and may be better suited to installations with very low or highly variable irradiance where speed range is constrained. This interconnection between pump type, motor properties and control strategy is another reason that the system-level, not component-level, perspective on efficiency optimization that is the focus of this review.

3. PV-Fed BLDC System SEPIC Converter.

3.1 Topology and Operating Principle

An SEPIC converter is made up of an input inductor, a coupling capacitor, an output inductor, power switch, a diode (or synchronous switch), and an output filter capacitor. With every switching cycle, energy is conducted into the load by the coupling capacitor with the input inductor keeping the PV array drawing constant current irrespective of the duty cycle at that moment. This continuous input current property is especially beneficial to PV interfacing as PV modules have a nonlinear currentvoltage characteristic that is ripple sensitive; a continuous low ripple input current through the converter enables the MPPT algorithm to better estimate and track the actual maximum power point, and the pulsating input current of a traditional buck or Zeta converter can bias operation at a point other than the MPP, and lower net energy harvest.

3.2 Benefits of SEPIC compared to Alternative Topologies.

The main merit of SEPIC in this system is that it can step up and step down the PV array voltage in a non-inverting topology with only one step. This is necessary since the open-circuit voltage of a PV array can be significantly greater or less than the voltage needed on the DC link to the motor, based on the irradiance, temperature, and the count of modules series-connected. Buck-only converters are unable to raise the voltage when there is a lack of irradiance and boost-only convertors are unable to lower the voltage when there is surplus voltage; in both scenarios, the converter will be operating out of the MPP at some point of the day, and this will lower the total energy yield. The Ćuk converter provides the same buck-boost range, but reverses the polarity of the output, making it harder to interface with traditional gate-drive and inverter circuitry. SEPIC does not have this complication but still has the buck-boost feature, so it is a balanced solution in the PV-fed BLDC pumping.

3.3 Design Considerations

The design of the SEPIC stage to be used in a solar pumping application must pay close attention to the choice of the input and output inductors to allow the mode to remain in a continuous conduction mode (CCM) at the anticipated range of irradiance as discontinuous conduction will add extra current ripple to the system and decrease the accuracy of the MPPT. The coupling capacitor should be large enough to accommodate the ripple current of the switching frequency and at the same time reduce the voltage droop when transferring energy. There is a trade-off between the size of passive components (preferring higher frequency) and the switching losses (preferring lower frequency) in switching frequency selection; several reported designs use the 20-100 kHz range to pump kilowatts. Since the duty cycle of the SEPIC converter is the most important actuation variable of MPPT, both the bandwidth and small-signal dynamics have a direct impact on the maximum tracking rate of the overall control loop, which motivates the use of intelligent controllers capable of adjusting the duty-cycle update rate to the irradiance rate of change.

4. Motor Drive and Control (BLDC motor drive)

4.1 BLDC Motor Fundamentals

The BLDC motor is a permanent-magnet synchronous motor with trapezoidal back-EMF, and powered by rectangular current pulses synchronized to rotor position by electronic commutation. A three-phase inverter bridge is used to switch stator windings on and off in sequence, controlled by a commutation logic circuit, rather than using a mechanical commutator and brushes, thus avoiding the use of a mechanical commutator and brushes. This design is more efficient (usually between 85 and 95 per cent in well designed drives), less electromagnetic interference, less acoustic noise and a much longer operating life (without maintenance) which is particularly important when pumps are remote or submerged and therefore hard to maintain.

4.2 ECS and sensorless Control.

Traditional BLDC commutation uses Hall-effect sensors embedded in the motor to give discrete rotor-position feedback at electrical 60-degree intervals, based on which the commutation sequence to be used by the inverter switches is computed. Although efficient, Hall sensors are more expensive, difficult to wire, and may present a failure point, especially in submersible pump systems where reliability of sensors subjected to long-term exposure to water is an issue. Sensorless commutation methods, where rotor position is determined by the back-EMF zero-crossing or the third-harmonic part of the terminal voltage or by state estimation based on the observer, have therefore found a fair share of research attention in the application of solar pumping. The use of intelligent sensorless methods, such as neural-network position estimators and sliding-Mode observers, has been described to provide consistent results of maintaining accurate commutation even with the low speeds and light loads of early-morning operation and late-afternoon operation of early-morning operation when the magnitude of the back-EMF is significantly smaller than that of the conventional back-EMF-based methods.

4.3.Speed and Torque Control Strategies

The quadratic relationship between torque and speed of centrifugal pump loads makes the control of speed and torque in BLDC-driven pumps difficult since both the torque and the current required increase substantially with the operating speed. The classical PI or PID controllers are common due to their simplicity that needs close tune gain and may show poor performance with the broad operating range that comes with the variable solar input. Policymaking alternatives, such as fuzzy PI controllers, model reference adaptive control and sliding-mode control, provide enhanced resistance to load and parameter variations, whereas model predictive control (MPC) can directly optimize switching behavior against efficiency and current-ripple goals, at increased calculation requirements.

4.4 Comparative discussion of drive strategies.

Based on the above discussion of drive strategies, the most commonly used drive strategy in commercial solar pumping products is classical Hall-sensor-based commutation with PI speed control because it is simple, well understood, and the tuning process is well understood, and because it has low computational requirement. Sensorless schemes of commutation do minimize the cost of hardware and enhance the reliability of submersible or other harsh-environment applications, but typically demand more advanced signal processing and may also have lower accuracy when starting and at very low speed. The use of intelligent drive strategies intelligent drive strategies: fuzzy, sliding-mode, and predictive control provide a better robustness to the broad operating range that is required by the nonlinearity of variable solar input and pump load, but at the expense of more complex design and computation. Which technique is unconditionally better is thus less important than the balance of cost, reliability and performance requirements of the target application, be it a small household drip-irrigation system or a larger community water-supply installation.

5. Maximum Power point tracking techniques.

5.1 Conventional MPPT Techniques

The most common algorithms that are still in use in MPPT are Perturb and Observe (P&O) and Incremental Conductance (INC) due to their simple nature and low computational cost. P&O works by periodically varying the converter duty cycle and monitoring the change in PV output power, and changing the direction of perturbation. Although P&O is easy to apply, its nature is to vibrate around the MPP in steady state and to lose track direction at fast changing irradiance and hence capture less energy. INC does better by measuring the instantaneous and incremental conductance of the PV array to directly estimate the direction of the MPP (in theory zero steady-state oscillation is possible; in practice sensor noise and quantization effects still cause a small ripple). Both approaches are also problematic in the case of partially shaded conditions when the powervoltage characteristic has a number of local maxima and the traditional hill-climbing methods are drawn to finding a local and not the global maximum.

5.2 Intelligent MPPT Techniques

Fuzzy logic MPPT overcomes the oscillation and slow-convergence drawbacks of traditional techniques through the employment of linguistic rules (usually expressed in the error and change-of-error of PV power) to adaptively decide the magnitude of the perturbation in the duty-cycle. Since the perturbation step size is large at large distances away MPP and small at nearby distances, fuzzy MPPT both converges quickly and has a low steady-state ripple, and does not need an explicit mathematical model of the PV array. Artificial neural network-based MPPT is data driven, where a network is trained offline (or adaptively online) to directly relate measured irradiance, temperature and array voltage/current to the optimum duty cycle or reference voltage; a well-trained ANN can track the MPP effectively in real time, but will not extrapolate well beyond its training envelope. ANFIS systems are fuzzy-based systems with interpretability and rule-based structure paired with the adaptive learning of neural networks, with gradient-based or hybrid learning used to automatically tune membership functions using data, and have been shown to be superior to either standalone fuzzy or ANN systems in tracking speed and steady-state accuracy.

5.3 Optimization-Based (Metaheuristic) MPPT

The PV powervoltage curve becomes multimodal under partial shading and gradient-based or rule-based algorithms have a risk of converging to a local maximum. The metaheuristic algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Grey Wolf Optimization (GWO), Cuckoo Search (CS) and Ant Colony Optimization (ACO) are population-based, meaning they are stochastic searches of the duty-cycle space, employing multiple candidate solutions which offer a much greater likelihood of arriving at the global maximum. Such methods usually provide better performance in partially shaded situations and for rapidly changing irradiance at the expense of higher computational cost and slower initial convergence than gradient-based methods at uniform irradiance. To compromise tracking speed with global-optimality guarantees, hybrid schemes have been suggested which use a fast conventional or fuzzy tracker to operate uniform-irradiance, and use a metaheuristic re-initialization when multiple peaks are detected.

6. Smart Control Architectures towards Improved Efficiency.

6.1 Fuzzy Logic Control

The wide use of fuzzy logic control (FLC) at both MPPT and motor-control stages of SEPIC-fed BLDC pumping systems has been enabled by its ability to encode expert information and cope with system nonlinearity without the need of having a system model. In a standard two-input, single-output setup, the error and change-of-error between actual and reference power (or speed) is fuzzified, compared to a rule base, and defuzzified to create a duty-cycle or PWM correction signal. FPLC has been extensively documented to minimise MPP tracking jitter and better dynamical response than P&O and INC, but is computationally feasible enough to be implemented on low-cost microcontrollers or digital signal processors commonly found in field-deployed pumping systems.

6.2 Artificial Neural Networks

Controllers based on ANNs use the universal function-approximation property of multilayer networks to directly learn, using data, complex, nonlinear relationships between environmental input (irradiance, temperature) and optimal control output (reference voltage, duty cycle or commutation timing) without the need to use analytical PV or motor models. The most common networks are trained by backpropagation and radial basis function networks, as well as recurrent networks, have also been experimented to exploit the temporal dynamics in the rapidly changing irradiance. An important practical consideration is that it must have representative training data that covers the entire variety of operating conditions that the system is going to be subjected to; where one does not have sufficient training data, there can be poor generalization, and worse performance in conditions that were not represented in the training.

6.3 ANFIS Hybrid Approaches

Adaptive Neuro-Fuzzy Inference Systems combine fuzzy if-then rule forms with neural network-like parameter learning, enabling the membership functions and rule consequents of a fuzzy controller to be optimised automatically based on input-output data instead of having to be specified by hand by experts. This hybridization usually provides a better rate of MPP convergence and reduced steady-state ripple as compared to either standalone fuzzy or ANN controllers, and still provides some interpretability that is missing in the purely black-box neural counterparts. Controllers based on ANFIS have been used to generate MPPT duty-cycle and to generate adaptive speed control to the BLDC drive, and improvements in efficiency have been reported especially during irradiance changes at a high rate due to intermittent cloud cover.

6.4 Sliding Mode and Model Predictive Control.

Sliding mode control (SMC) is highly robust to the uncertainty of parameters and external disturbance by driving the system state to an a priori sliding surface and holding the system state to that surface by a high-frequency switching control action. Applied to SEPIC duty cycle or BLDC current loop, SMC could offer rapid, strong regulation which is not very sensitive to the PV array or motor parameter change, although chattering high-frequency oscillation along the sliding surface is a practical issue which has prompted variants of the sliding mode based on higher-order variants. Model predictive control (MPC) poses the control problem as a finite-horizon optimization, choosing the switching action that minimizes a cost function (e.g., tracking error, switching frequency, current ripple) with constraints on the system. The capability of MPC to directly integrate various goals and constraints can be appealing to the coordinated control of SEPIC-BLDC, but the computational cost has historically restricted its use to relatively powerful embedded processors.

6.5 Bio-Inspired and Metaheuristic Optimization.

In addition to MPPT applications, the bio-inspired optimization algorithms have found offline applications to optimization of controller gains (e.g., PI, fuzzy membership functions, ANN weights) to minimize a specified performance index such as integral of time-weighted absolute error (ITAE) or energy loss over a representative irradiance profile. It has been reported that genetic algorithms, particle swarm optimization, and more recent nature-inspired analogs (grey wolf, whale, cuckoo search and firefly algorithms) can serve this purpose, with the parameter controllers of the algorithms typically performing better than tuned analogs, especially when the tuning goal includes consideration of the wide operating range that is experienced in solar-powered applications.

6.6 Intelligent Controllers Comparative Discussion.

Combined, the intelligent control methods discussed in this section fill in the complementary shortcomings of traditional control. The balance of simplicity of implementation and performance improvement allowable by fuzzy logic control is most favourable, so it is often used as an initial step in the progression of conventional P&O/INC and PI control in reported designs. Where adequate training data exists to support the steady-state accuracy of ANN and ANFIS methods, these methods are superior in tracking speed and steady-state performance but have a data-dependency and generalization issue since the rule-driven systems of fuzzy systems are expert-knowledge-driven, not data-driven. Model predictive control and sliding mode offer the most robustness guarantees in theory, and are especially well-adapted to applications where there is much uncertainty about the parameters, or multiple control goals being pursued simultaneously, at the cost of increased computational effort. It is characterized by a specific performance in the case of partial shading, where the multimodal structure of the PV power curve is a formidable obstacle to the local-search-based approach, whether they are conventional or intelligent in character. Practically, however, there have been numerous reported designs which are hybrids of one or more of these strategies - such as a fuzzy or ANFIS controller to handle day-to-day operation with periodically re-optimized metaheuristics to detect and avoid local maxima caused by partial shading - as part of a wider trend towards hybrid intelligent control architectures.

7. System Level Integration and Control Architecture.

The enhancement of energy-efficiency in SEPIC-fed BLDC solar pumping systems needs to be operated in a coordinated manner that involves three interacting loops, an outer MPPT loop to adjust the SEPIC duty cycle to capture the maximum available PV power, an inner voltage/current regulation loop to provide converter stability and component stress limits, and a motor-control loop to adjust BLDC speed or torque based upon the power available at the PV-SEPIC stage, and the load characteristics of the pump. Figure 1 provides the complete system architecture that depicts the PV array, SEPIC converter, inverter/commutation stage, BLDC motor, and centrifugal pump along with sensing and intelligent controller blocks that complete the MPPT and motor-control loops.

Figure 1. Block diagram of the SEPIC-fed BLDC solar PV water pumping system

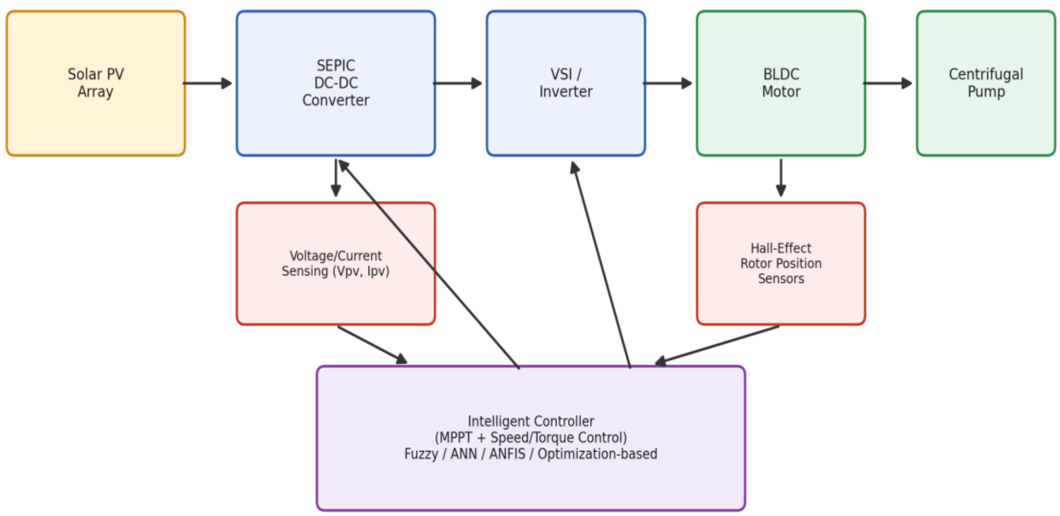

Figure 1. Block diagram of the SEPIC-fed BLDC solar PV water pumping system

In the majority of published architectures, the intelligent controller computes the MPPT algorithm based on the measured PV current and voltage to provide a duty-cycle signal to the SEPIC switch, and a separate (or combined) control block computes the commutation signals to the inverter and provides feedback control over the motor speed based on the available power. The resultant load-speed characteristic of the pump is that pump load torque is proportional to the square of speed, thus the attainable operating point of a pump is a joint function of the PV-SEPIC maximum power characteristic and the pump affinity-law load curve; smart controllers with such an understanding of the interaction have been shown to yield higher daily water-yield than controllers treating MPPT and motor control as a decoupled problem.

8. Comparative Analysis

The following section provides a concise comparison between the MPPT techniques and converter topology as discussed in the previous sections with the aim of assisting in the selection of techniques to apply depending on the specific application needs. Table 1 discusses the conventional and intelligent methods of MPPT in terms of tracking speed, steady-state ripple and implementation complexity and Table 2 discusses SEPIC in comparison to other DC-DC converter topologies that are often considered in PV interfacing.

Table 1. Comparison of MPPT Techniques for SEPIC-Fed BLDC PV Pumping Systems

MPPT Technique	Principle	Tracking Speed	Steady-State Ripple	Implementation Complexity

Perturb & Observe (P&O)	Perturbs duty cycle and observes power change direction	Moderate	High under fast irradiance change	Low
Incremental Conductance (INC)	Compares instantaneous and incremental conductance	Moderate	Moderate	Low–Medium
Fuzzy Logic Control (FLC)	Rule-based reasoning on error and change-of-error of power	Fast	Low	Medium
Artificial Neural Network (ANN)	Learns nonlinear V-I-P mapping from training data	Fast	Low	Medium–High
ANFIS (Fuzzy–Neural Hybrid)	Combines fuzzy inference with neural adaptive learning	Very Fast	Very Low	High
Particle Swarm Optimization (PSO)	Swarm-based stochastic search for global MPP	Fast (global search)	Low	High
Grey Wolf / Cuckoo Search / ACO	Nature-inspired metaheuristics for multi-peak tracking under partial shading	Fast (global search)	Low	High

Table 2. Comparison of DC-DC Converter Topologies for PV-BLDC Interfacing

Converter	**Voltage Conversion**	**Input Current**	**Polarity**	**Suitability for PV-BLDC Pumping**
Buck	Step-down only	Pulsating	Non-inverting	Limited; cannot boost during low irradiance
Boost	Step-up only	Continuous	Non-inverting	Limited; no buck capability for high irradiance
Ćuk	Step-up/Step-down	Continuous	Inverting	Good dynamics but output polarity inversion complicates drive design
SEPIC	Step-up/Step-down	Continuous	Non-inverting	Excellent: wide MPPT range, low PV current ripple, non-inverted output ideal for BLDC front end
Zeta	Step-up/Step-down	Pulsating	Non-inverting	Comparable range to SEPIC but higher input ripple reduces PV utilization

As the results in Table 1 summarize, intelligent MPPT methods tend to have higher implementation complexity at the price of faster tracking and lower steady-state ripple compared to traditional P&O and INC methods, with the weakest performance but most powerful performance of hybrid ANFIS and metaheuristic methods. Table 2 substantiates the fact that SEPIC provides a desirable balance between buck-boost voltage range, continuous input current, and non-inverting output polarity, unlike single-direction (buck, boost) and inverting (Ćuk) options, and the reason it is becoming more popular in recently reported PV-BLDC pumping models.

Figure 2 gives a classification summary of the survey of intelligent control methods discussed in this review, by underlying methodology (fuzzy logic, neural/ANFIS, bio-inspired optimization and sensorless/adaptive control) along with an indicative list of reported advantages of each group of methods.

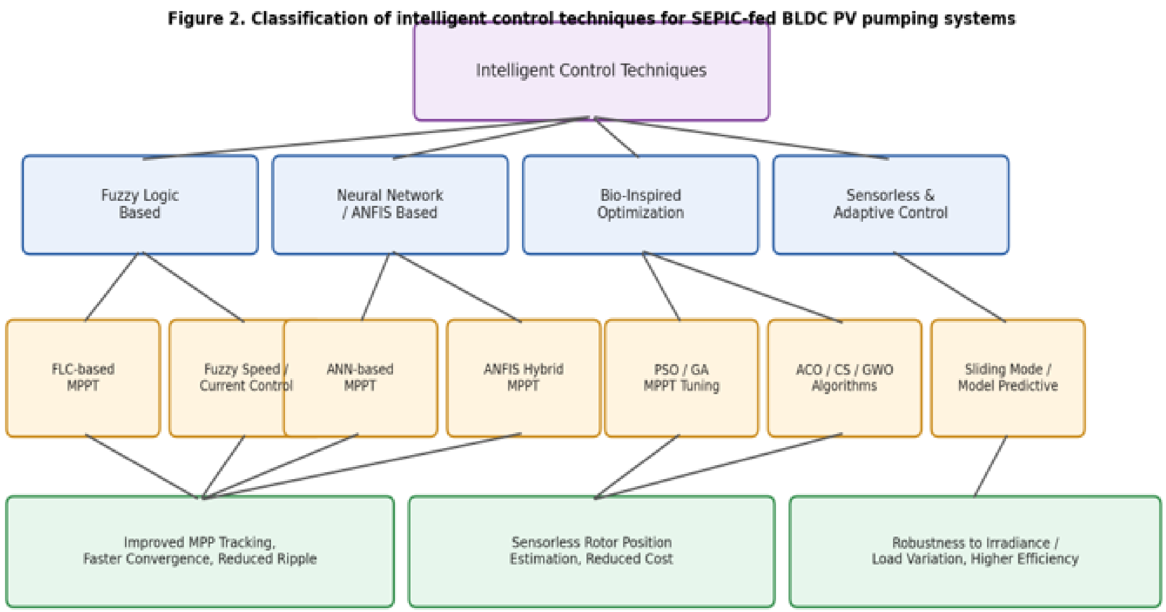

Figure 2. Classification of intelligent control techniques for SEPIC-fed BLDC PV pumping systems

9. Energy Saving Methods.

9.1 Converter-Level Efficiency Measures

Switching losses, conduction losses and magnetic core losses in the SEPIC stage affect the energy efficiency at the converter level. Soft-switching methods, synchronous rectification (in place of SEPIC diode with an actively-controlled switch), and optimal choice of switching frequency in consideration of passive component size have been reported to produce quantifiable efficiency improvements. Smart duty-cycle control that reduces the amount of avoidable switching transitions during irradiance periods of constant irradiance can also reduce switching losses as compared to fixed-step conventional MPPT.

9.2 Motor-Level Efficiency Measures

On a motor level, conversion efficiency between electrical and hydraulic power is directly enhanced by minimizing commutation torque ripple, due to non-ideal trapezoidal back-EMF, finite current-commutation time, and cogging torque. The strategy of advanced commutation such as current-shaping and predictive commutation-instant adjustment have been reported to minimize the torque ripple and related vibration and acoustic noise, indirectly increasing the pump bearing and seal life, as well as enhance instantaneous efficiency.

9.3 System-Level Coordination

In addition to optimization of the separate components, with the MPPT reference coordinated with the affinity-law characteristic of the pump, the system can run nearer to its combined efficiency optimum, over the entire daily range of irradiance variation, than would be possible when the PV-side and motor-side efficiency are optimized separately. Recent literature has described intelligent supervisory control layers such as fuzzy or ANN-based coordinators that modify the speed reference based on the available solar power as well as pump operating constraints (e.g., minimum flow rate, maximum head) to achieve greater daily water output than systems designed with fixed or independently tuned MPPT and speed-control loops.

9.4 Reported Efficiency Improvements

Although specific quantitative benefits differ across reported studies based on system rating, climate and pump characteristics, the overall trend in the literature reviewed suggests that intelligent MPPT (fuzzy, ANN, ANFIS) methods tend to incur less loss in MPP tracking compared to conventional P&O/INC methods, especially in partially shaded systems and where irradiance varies rapidly, whereas sensorless and adaptive BLDC control schemes tend to incur less loss in sensor, and enhance low-speed/ light-load performance compared to fixed-gain PI control. All these enhancements are said to result in reasonable increases in daily water-pumping rate of a given size of PV array, enhancing the techno-economic feasibility of solar pumping over diesel options.

9.5 Techno-Economic Considerations

The economic benefits of energy-efficiency provided by intelligent control eventually result in the following two ways: a decrease in the size of PV array and pump capacity needed to achieve a desired daily water-yield target and an increase in the amount of water yield that can be obtained with an existing system in place. The scale of this economic goodwill is closely linked to location-specific considerations, such as the variability of the local solar resource, the commonness of partial shading (by surrounding vegetation or buildings) and the premium attached to incremental water supply at times of peak growing or dry-season demand. The incremental hardware and engineering cost of an intelligent controller, and the incremental processing power of an intelligent controller (or the incremental processor power of an intelligent sensor), may be offset against the estimated efficiency improvement and a corresponding value of water-yield or fuel-displacement over the operating life of the system, due to the fact that intelligent controllers usually demand more processing power or sensor power than standard PI/P&O implementations. This lifetime-oriented assessment is relatively underrepresented in the literature that is reviewed compared with the large body of work in control-algorithm performance itself, a real-world gap between the achieved technical performance and field-deployment decision-making.

10. Problems and Research Gaps.

- Computational cost: Advanced intelligent controllers (ANN, ANFIS, MPC, metaheuristic optimization) need more processing power than standard PI or hill-climbing solutions that can be expensive to implement (can add to system cost) or can force tradeoffs in the attainable sampling rate on low-cost embedded platforms that are commonly used in deployed pumping systems.
- Training data and generalization: Data-driven methods (ANN, ANFIS) need representative training data over the entire range of irradiance, temperature, and load conditions; and their operation can be poor under those conditions not well-represented in the training set, and few studies have been reported to adapt online to long-term PV degradation or seasonal variation.
- Sensorless control reliability: Sensorless commutation is cheaper, and eliminates a component that is prone to failure, but its operation at very low speed and light load (both frequently encountered in early morning operation and late afternoon operation) remains a subject of research, with back-EMF-based techniques showing lower accuracy in this regime.
- Standardization and benchmarking: There is no standardized benchmark of irradiance/load profile that various intelligent control techniques can be compared directly against in the literature, and efficiency comparisons across studies across different techniques are challenging, which makes it difficult to compare techniques when practitioners are selecting one.
- Techno-economic analysis Relatively few studies have given such a lifecycle cost-benefit analysis to balance the incremental efficiency benefits of intelligent control with the incremental hardware, development and maintenance costs incurred, especially to relatively small installations such as those on smallholder and community scales where the issue of capital cost sensitivity is acute.
- Resistance to component aging and faults: Intelligent controller robustness to converter component aging, PV degradation, and partial motor winding faults are not studied as well as nominal-condition performance analysis.
- Field validation and simulation A large fraction of the literature presented to date confirms intelligent control methods proposed by simulation or scaled laboratory experiments but does not investigate how these methods would operate with dust accumulation on the grid, across temperature limits, or with variable power quality independent of the grid.
- Interoperability with current infrastructure Practical implementation of more sophisticated intelligent controllers is made complex by the fact that they need to be compatible with available inexpensive commercial pump and inverter hardware that may not provide the sensing or actuation interfaces needed by more advanced control designs without hardware modification.

11. Future Research Directions

The directions mentioned above seem to have potential to promote the state of the art in the intelligent control of SEPIC-fed BLDC solar PV water pumping systems. First, a pragmatic way to higher performance is through hybrid intelligent controllers based on the computational efficiency of traditional approaches and the robustness of intelligent methods, such as fuzzy-assisted P&O or metaheuristic-initiated fast local search. Second, the increasing access to low-cost, high-performance embedded processors and edge-AI accelerators is likely to decrease the practical threshold to the implementation of ANN, ANFIS, and MPC-based controllers in field installations. Third, digital-twin systems with a constantly updated virtual representation of the physical pumping system can provide the possibility of predictive, condition-aware control that predicts irradiance variations (with short-term solar forecasting) and pump degradation instead of responding to them. Fourth, remote monitoring and control of the Internet-of-Things (IoT) may facilitate centralized optimization and predictive maintenance of full fleets of pumping installations, which is a field with limited existing coverage in the literature reviewed. Ultimately, a standardized experimental benchmark and open datasets are still desired that would enable rigorous and reproducible comparative analysis of intelligent control methods among research groups and would speed the translation of laboratory findings into field-deployable solutions.

In addition to the above-mentioned algorithmic improvements, materials and component-level innovations will also tend to affect future designs of SEPIC-fed BLDC pumps. The growing availability of wide-bandgap power semiconductors (silicon carbide and gallium nitride) can support higher switching frequencies at lower losses, which may permit the passive components of the SEPIC stage to be made smaller and less expensive and also alleviate the bandwidth constraints currently limiting the rate of MPPT updates achievable. In a similar fashion, improvements in materials based on rare-earth-free or reduced-rare-earth permanent-magnets can also affect the cost and supply-chain resilience of BLDC motors in large-scale rural electrification programmes, an economic factor that, although it is not directly under the control-system researcher's control, will condition the practical environment in which such control methods are eventually applied.

11.1 Nomenclature and Abbreviations

- PV — Photovoltaic
- SEPIC — Single-Ended Primary Inductor Converter
- BLDC — Brushless Direct Current (motor)
- MPPT — Maximum Power Point Tracking
- MPP — Maximum Power Point
- P&O — Perturb and Observe
- INC — Incremental Conductance
- FLC — Fuzzy Logic Control
- ANN — Artificial Neural Network
- ANFIS — Adaptive Neuro-Fuzzy Inference System
- PSO — Particle Swarm Optimization
- GA — Genetic Algorithm
- GWO — Grey Wolf Optimization
- SMC — Sliding Mode Control
- MPC — Model Predictive Control
- PMDC — Permanent Magnet Direct Current (motor)
- SPWPS — Solar PV Water Pumping System

12. Conclusion

This review has presented the current knowledge on intelligent control of SEPIC-fed BLDC solar PV water pumping systems, including converter topology choice, motor drive control, maximum power point tracking, and system-level integration. The broad buck-boost capability, continuous input current, and non-inverting output of the SEPIC converter combine with intelligent control methods, such as fuzzy logic, artificial neural networks, ANFIS, sliding mode control, model predictive control and bio-inspired metaheuristic optimization, to make it a highly-suited interface to BLDC-driven pumping loads, and to provide intelligent control methods with meaningful improvements in MPP tracking speed, steady-state ripple and robustness compared to conventional methods, especially when only partial shading or rapidly-varying irradiance conditions are to be addressed. Simultaneously, the literature review shows that the issues concerning computational load, the reliability of sensorless control at low speed, benchmarking, and techno-economic assessment as a whole remain a challenge. These challenges can be met by means of hybrid intelligent controllers, digital-twin-based predictive control and standardized open benchmarks, which is a promising area of future research, and can potentially enhance the efficiency, reliability and economic feasibility of solar-powered water pumping to irrigate fields and supply rural water.

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