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RESEARCH ARTICLE - ENGINEERING (MISCELLANEOUS)

Optimization of Photovoltaic Water Pumping Systems: Progress, Limits, and Prospects for a Healthy Energy Future

Alain Foutche Tchouli[1, 2], Stephane Ngasop Ndiya[1], Hilaire Tchami[1], Claude Bertin Nzoundja Fapi[3, 4*], Hyacinthe Tchakounté[2]

[1]Department of Electrical, Energetic and Automatic Engineering, National School of Agro-industrial Sciences, University of Ngaoundere, Ngaoundere, Cameroon

[2]LESIA Laboratory, National School of Agro-industrial Sciences, University of Ngaoundere, P.O. Box: 454 Ngaoundere, Cameroon

[3]GREAH Laboratory, University of Le Havre Normandie, 75 Bellot Street, 76600 Le Havre, France

[4]LIED Laboratory, IUT de Paris Pajol, 20 rue du département, University Paris Cité, 75018, Paris, France

[*] Corresponding author E-mail: nzoufaclauber@yahoo.fr

Article Info.	Abstract
Article history: Received 02 August 2024 Accepted 17 October 2024 Publishing 31 March 2025	Today, water pumping plays a crucial role throughout the world, due to its many uses, such as irrigation, watering livestock and supplying water for domestic needs in isolated areas not served by traditional distribution networks (of water and/or electricity in general). The use of photovoltaic solar energy offers promising, environmentally friendly prospects for pumping water in these regions. However, several factors limit the performance of these pumping systems. To achieve this goal, a significant amount of work is underway to optimize the efficiency of these photovoltaic water pumping systems. In this study, various methods for enhancing pumping system efficiency are analyzed, such as the maximum power point tracking (MPPT) methods used, highlighting their respective advantages and limitations, as well as hydraulic system architectures. The aim is therefore to suggest research proposals for improving the energy efficiency of photovoltaic water pumping systems, with a view to promoting the transition to a more environmentally friendly and sustainable energy future.

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Keywords: Photovoltaic Pumping Systems; MPPT; Energy Efficiency; Energy Future; Limiting Factors.

1. Introduction

Today, pumping water is an essential operation throughout the world. This is due to the many uses of water, such as irrigation, watering livestock, supplying water to remote areas for domestic needs, and many more. In 2019, WHO and UNICEF agreed that 2.2 billion people worldwide still lack access to safe, continuous drinking water. According to a report published in 2023, by the NGO Mains Unies d’Afrique (MUA) on the water situation in Cameroon in particular, 34% of the population (just over 10 million inhabitants) has no access to drinking water. The situation is even more worrying in rural areas of Cameroon, where over 55% of the population has no access to drinking water, often relying on rivers and marigots as their sole source of supply. According to this study, the northern part of the country (Adamaoua, North and Far North) is the area most affected by this problem of access to drinking water, with over 55% of inhabitants without access to this resource. However, this zone has a significant solar resource of 5.8 $kWh/m^2/day$ and considerable hydraulic potential. If these resources are effectively exploited, water problems could be solved definitively and sustainably.

Thanks to the significant reduction in the cost of solar energy in recent years, this clean, renewable energy is finding widespread use in water pumping throughout the world, offering an excellent alternative for developing countries like Cameroon. Cameroon’s energy transition, governed by the Electricity Law of December 14, 2011, focuses on replacing fossil fuels with renewable, environmentally friendly energy sources, particularly for water pumping. This transition offers numerous benefits: environmental sustainability through decarbonization of the energy mix and mitigation of the effects of climate change; accessibility and cost reduction; empowerment of communities by eliminating dependence on external and costly energy sources, such as diesel generators; and positive socio-economic impact by stimulating the local economy through job creation in the installation, maintenance and operation of solar systems [1].

Nomenclature & Symbols

CS	Cuckoo Search	PV	Photovoltaic
FLC	Fuzzy Logic Controls	PWPS	Photovoltaic Water Pumping Systems
G	Global Solar Irradiance	Q	Charge of the Electron
Gref	Nominal Irradiation at STC	RS	Series Resistance
IM	Induction Motor	Rsh	Shunt Resistance
InC	Incremental of Conductance	SEPIC	Single Ended Primary Inductor Converter
Iph	Photo Generated Current	STC	Standard Test Conditions
Isc	Short-Circuit Current	Tref	Nominal Temperature at STC
K	Boltzmann	Voc	Cell’s Open-Circuit Voltage
MPP	Maximum Power Point	Vt	Thermal Voltage
MPPT	Maximum Power Point Tracking	WP	Water Pumped
P&O	Pertub & Observe	PSO	Particle Swarm Optimisation
PS	Pump Systems		

Indeed, the conversion of solar radiation has been no secret since 1953, with the creation of the first photovoltaic cell. As a result, photovoltaic generators are the main component of any photovoltaic solar system [2], including many applications such as water pumping. However, this technology still presents challenges in terms of cost: although prices have fallen considerably in recent years, the initial investment cost for a photovoltaic pumping system remains high. In addition, the performance of solar systems is highly dependent on atmospheric conditions [3], posing persistent technical challenges, and particularly in areas with very aggressive climates [4], such as northern Cameroon, where temperatures can reach peaks of 40°C in the shade. The aim of this study is to analyze the work carried out around the world, particularly on photovoltaic water pumping. It would be wise to consider:

- The use of a variable-step inc-FLC to extract maximum power at any time and especially under rapidly changing conditions.
- Consider the use of pumped water (which has the peculiarity of having a very low temperature) to cool and even clean the panels making up the PV generator mounted on a solar tracker.

The paper is structured as follows: Section 1 presents a general overview of pumping systems. Section 2 will review various works on pumping systems, highlighting their advantages and limitations. In Section 3, emphasis will be placed on the techniques used to date to improve the efficiency of photovoltaic pumping systems, particularly those for water pumping. The conclusion of this work, together with suggestions for further research, will be presented in section 4.

2. Pumping Systems: History, Design and Operating Principles

Since research into pumping systems began in the 1960s, the quantity and quality of pumping system components have continued to evolve. Two pumping system architectures soon emerged: accumulator battery pumping systems, which were quickly superseded due to their high implementation and maintenance costs [5], and solar-powered pumping systems, which are the subject of much research today. The main components of a photovoltaic pumping system are: a photovoltaic generator, one or more DC-DC and/or DC-AC static converters (depending on whether a DC or AC motor and/or batteries are used), a pumping subsystem (motor-pump), a water reservoir, and a water source (well, borehole, etc.) [6], as illustrated in Fig. 1.

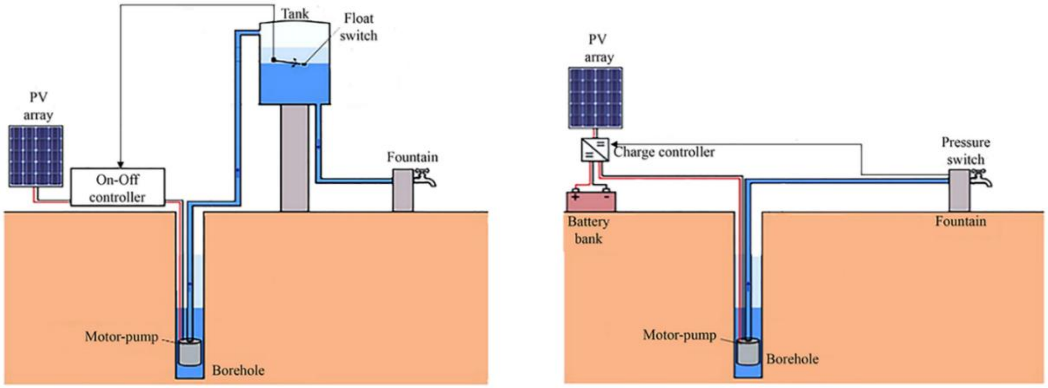


Fig. 1. Topologies of photovoltaic pumping systems: solar-powered and battery-powered systems [7]

As shown in Fig. 1, two distinct topologies of photovoltaic pumping systems are shown: the first is a solar-powered pumping system that only allows water to be pumped during the day, with low maintenance costs and a long service life. The second is a pumping system with a storage battery that allows water to be pumped at any time, even at night, with high maintenance costs and a shorter service life, as shown in the work of [7].

2.1. The photovoltaic generator

It is the main component of any photovoltaic (PV) system and is responsible for converting solar energy into electrical energy (direct current). The PV cell is the basic unit in this process, and its circuit is depicted in Fig. 2. In the literature, a PV cell can be modeled in two ways: either by the one-diode model, or by the two-diode model. The one-diode model is the most used [8, 9] due to its accuracy and simplicity.

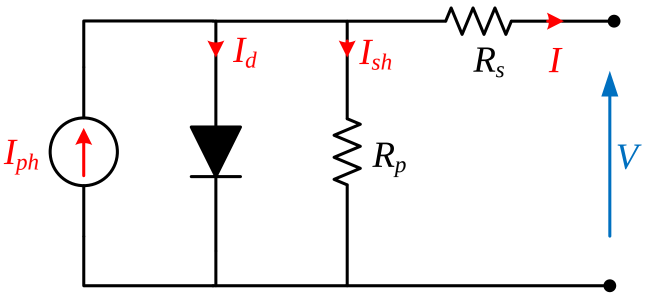


Fig. 2. Single-diode model of a PV cell [9]

Applying Kirchhoff's law (law of nodes) to the circuit in Fig. 2 allows us to obtain the expression for the current delivered by the PV cell is denoted by Eq. (1). [8, 9].

$$I = I_{Ph} - I_0\left(exp\left(\frac{V+RsI}{n.V_t}\right) - 1\right) - \frac{V+Rs.I}{Rsh} \tag{1}$$

The relation of the thermal voltage V_t is donated by Eq. (2).

$$V_t = \frac{kT}{q} \tag{2}$$

where k is the Boltzmann constant, q is the elementary electronic charge and T is the current temperature.

As far as the photo-generated current I_{ph} is concerned, it has been proven that it depends on solar global irradiance and the PV surface temperature and as can be noticed in the mathematical relation given by Eq. (3).

$$I_{Ph} = [I_{sc} + k_{sc}[T - T_{ref}]\, {}^{G}/_{G_{ref}} \tag{3}$$

G is the global solar irradiance, I_{sc} is the short-circuit current, k_{sc} is the temperature coefficient related to the current, T is the current temperature and G_{ref} is the reference value of the solar global irradiance in STC (1000 W/m^2), T_{ref} is the STC reference value of the PV surface temperature.

The diode reverses saturation current (I_0) is given by Eq. (4):

$$I_0 = \frac{\mathrm{I_{sc}+k_{sc}(T-T_{ref})}}{\mathrm{exp\{[V_{oc}+k_{oc}(T-T_{ref})]/n}V_t\mathrm{N_{sc}\}-1}} \tag{4}$$

where, k_{oc} is the temperature coefficient related to the voltage and V_{oc} is the cell's open-circuit voltage at the nominal conditions.

Thus, for N_p cells in parallels and N_s cells in series, the Eq. (1) above can be generalized as follows [8, 10, 11].

$$\mathrm{I = Np}\left(\mathrm{I_{Ph} - I0}\left(\mathrm{exp}\left(\frac{V+RsI}{Ns.n.Vt}\right) - 1\right) - \frac{V+Rs.I}{Ns.Rsh}\right) \tag{5}$$

where I_{ph} is the photo generated current R_s is the series resistance and R_{sh} is the shunt resistance.

Fig. 3 illustrates the existential links between a PV cell, a PV panel and a PV generator/field, as well as the associated characteristic electrical quantities.

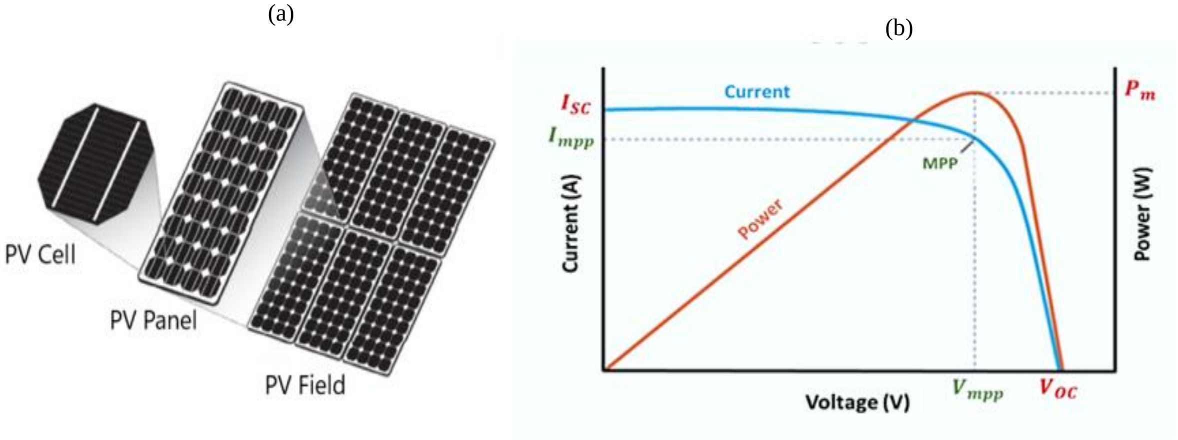


Fig. 3. (a) Existential Links between a PV Cell, PV Panel, and PV Generator/Field, (b) Ideal I-V and P-V Characteristics [12]

The performance of a PV cell is mainly and strongly linked to two physical quantities: temperature and irradiance [13]. The Fig. 4 shows the influence of these two variables on the I-V and P-V characteristics of a PV panel. Looking at Fig. 4, it's clear that, at constant surface temperature and variable solar irradiance, the short-circuit current (I_{sc}) of a photovoltaic panel is directly related to irradiance, while the open-circuit voltage (V_{oc}) varies negatively. According to [10], when irradiance is constant at 1000 W/m^2 and variable temperature, V_{oc} voltage is inversely proportional to temperature and *Isc* current is essentially constant. According to [12], there are other factors that limit the efficiency of photovoltaic panels (particularly during the operating phase), such as ambient air speed and temperature, panel orientation, ambient humidity and the incidence of soiling [14-20].

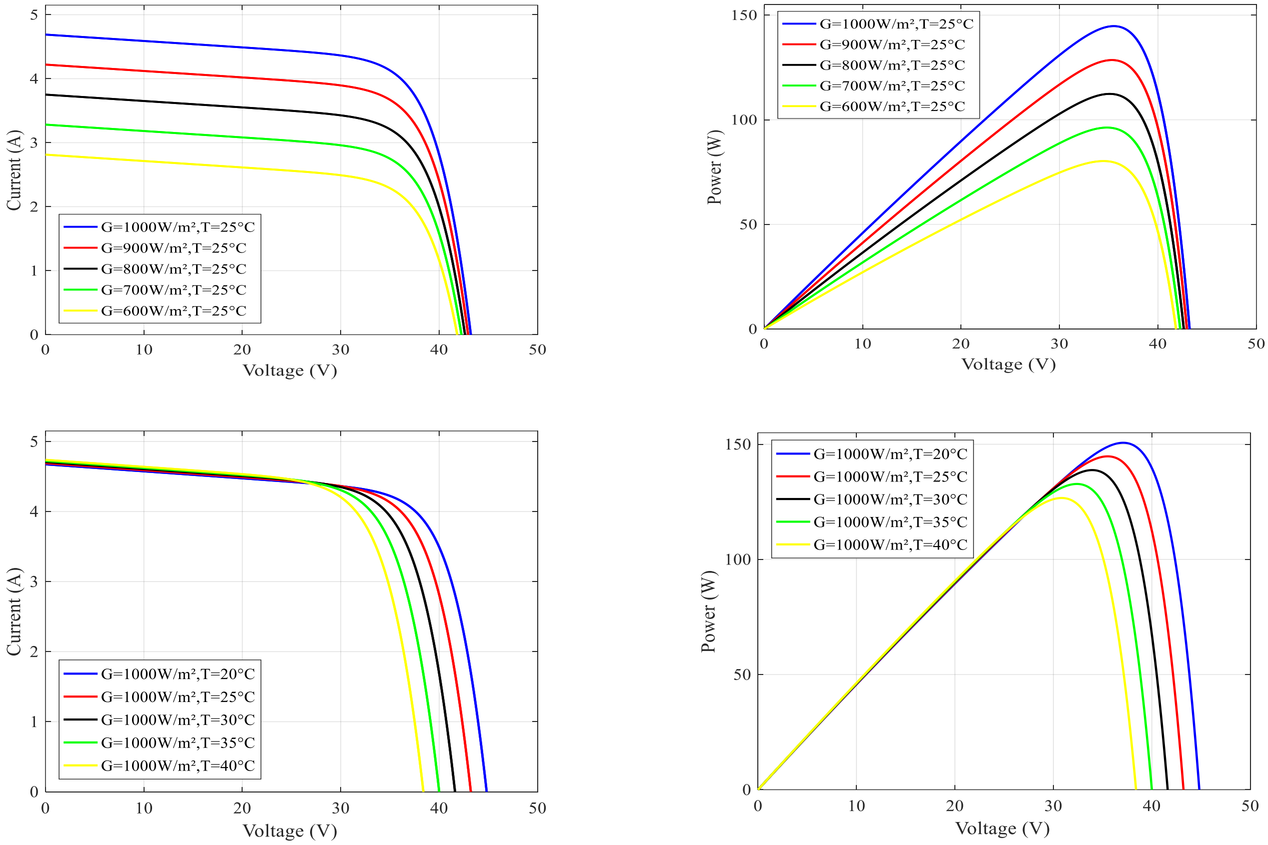


Fig. 4. Influence of irradiance and temperature variations on the I-V and P-V characteristic of a 150Wp PV panel [9]

2.2. Static converter

Static converters are essential in conditioning power from generation to consumption, with their type and configuration based on the specific design of the photovoltaic pumping system. DC-DC converters adjust voltage levels and optimize the maximum power point (MPPT) for systems using DC motors, enhancing efficiency. DC-AC converters convert the direct current from photovoltaic panels into alternating current for AC motors, compatible with standard pump motors and equipment. Depending on the pumping system's topology, a combination of these converters may be employed to meet site-specific requirements and optimize performance, as shown in Fig. 5.

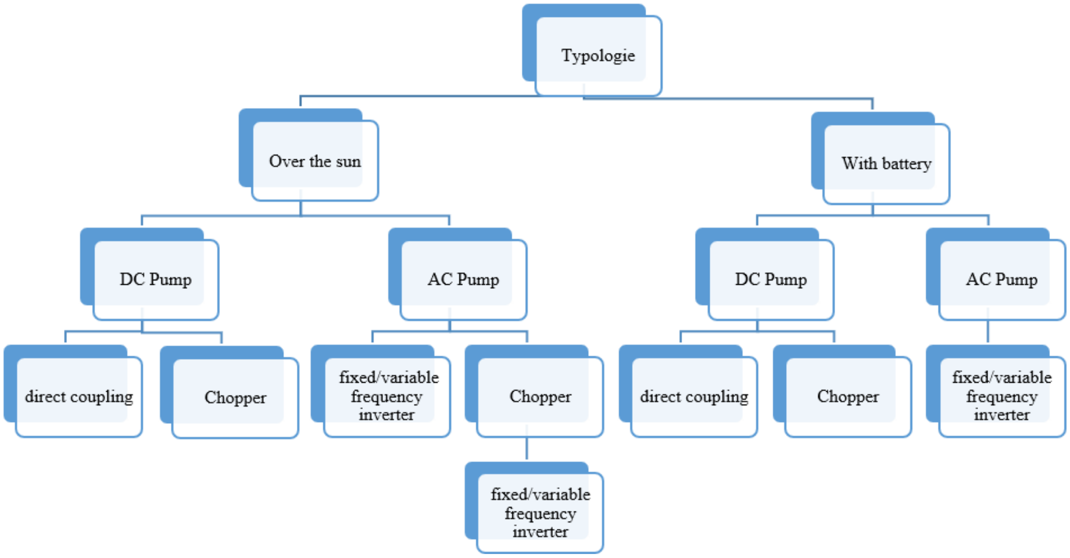
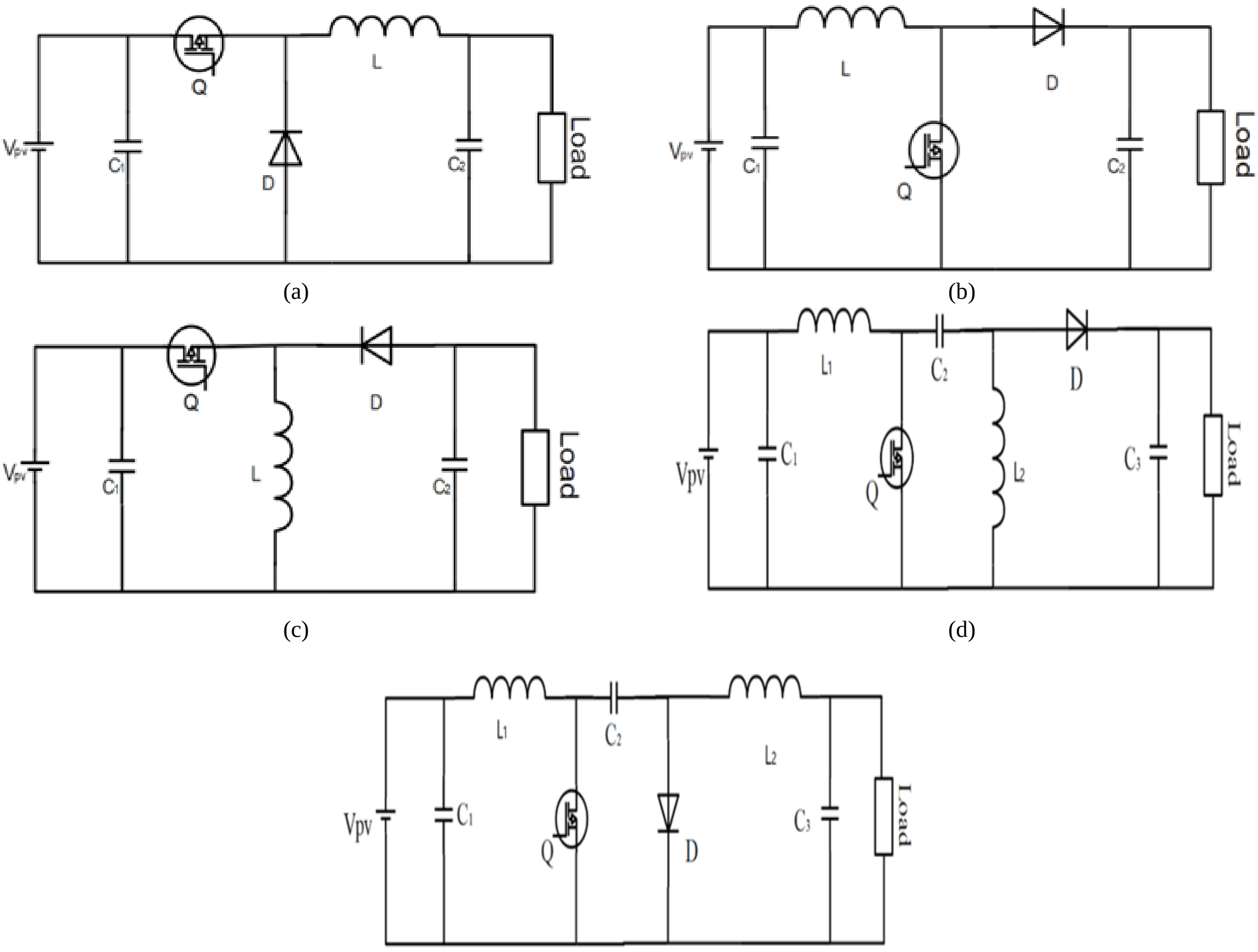


Fig. 5. Inverter selection flowchart based on pump type

2.2.1. DC-DC converters

According to [20] for optimal energy transfer in a solar photovoltaic system, the photovoltaic generator should always operate at the maximum power point (MPP) of its I-V curve. This requires a matching stage, typically a DC-DC converter, to optimize energy transfer [14]. Depending on system needs and environmental conditions, the converter may increase (boost), decrease (buck), or adjust voltage in both directions (buck-boost) [15]. Advanced MPPT algorithms further improve efficiency by dynamically maintaining the MPP. The choice of converter also affects both energy efficiency and economic considerations, as illustrated by the schematic diagrams in Fig. 6.



(a) (b)

(c) (d)

(e)

Fig. 6. Basic chopper circuits: (a) Buck, (b) Boost, (c) Buck-Boost, (d) SEPIC, (e) Cuk [15]

2.2.2. DC-AC converters

They are used in AC systems. There are two main types of inverters used in photovoltaic pumping systems:

- Fixed frequency inverter

Its use in pumping systems requires the interposition of a storage battery between the photovoltaic generator and the inverter. In this way, the battery voltage determines the inverter voltage, which represents the system's operating voltage.

- Variable frequency inverter

In this inverter, variable frequency signals proportional to the power supplied by the photovoltaic generator are fed to the pump motor, as illustrated in Fig. 7. So, if solar irradiance increases, the inverter automatically increases the frequency. This leads to an increase in pump speed and, consequently, an increase in pumping power and flow rate, and vice versa when solar irradiance decreases [18, 13]. These are the most widely used inverters in photovoltaic pumping [19, 20].

2.3. The motor

These are electromechanical converters that transform electrical energy into mechanical energy to drive the pump that extracts water from the source to points of use and/or storage.

2.3.1. DC Motor

For a photovoltaic solar pumping system, the choice of a DC motor is first and foremost an economical solution [20], as the photovoltaic generator supplies DC power, thus avoiding the need for a static DC/AC converter. This type of motor is used for pumping applications in small areas and at low power levels.

2.3.2. AC motor

There are also systems that use AC motors. Their advantages include high availability, robustness and low maintenance costs. However, they require the use of an inverter. They are used for high-power applications [21].

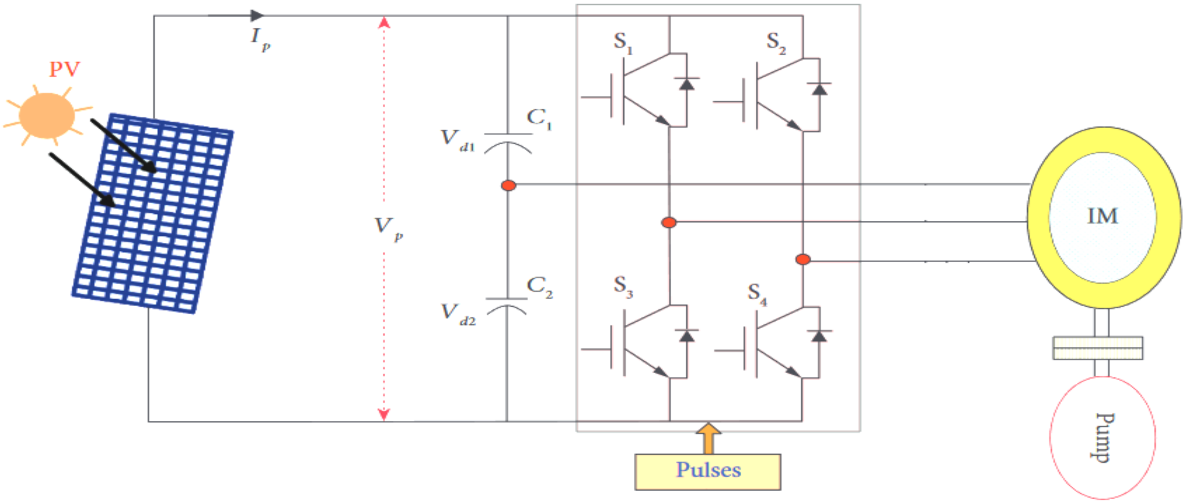


Fig. 7. Structure of a four interrupter three-phase inverter [19]

2.4. The Pump

Pumps are used for pumping liquids. There are two main types of pumps: positive-displacement pumps and centrifugal pumps. Also, depending on the physical location of the pump, in relation to the fluid being pumped, we can also distinguish two other types of pumps: the suction pump and the discharge pump [22]. The motor and pump are usually assembled and come in a variety of forms, as illustrated in Fig. 8.

a

b

Fig. 8. Some types of motor pump units: (a) submissive motor pump unit, (b) surface motor pump unit [23]

3. Review of the Literature on Pumping Systems: Advances, Advantages and Limitations

Photovoltaic pumping systems are made up of equipment from various fields of engineering. The water pump and part of the electric motor, resulting from mechanical engineering, ensure the movement of the water. Photovoltaic panels capture solar energy, while converters (such as inverters, pump controllers and charge controllers) and batteries are essential components of electrical and electronic engineering, managing energy conversion and storage. In addition, maximum power point tracking (MPPT) algorithms, developed within the framework of computer engineering, optimize system performance by adjusting the way solar energy is captured and used. This interdisciplinary between mechanical, electrical, electronic and computer engineering has enabled researchers to significantly improve the performance, cost-effectiveness and maintainability of these complex systems. Table 1 summarizes a critical and detailed analysis of several works on improving the performance of pumping systems.

Table 1. Summary of work reviewed

References	Method	Results	Limits and Perspectives
[5]	Use of a particular architecture of the P&O algorithm to control a boost converter feeding a pump to provide constant flow and pressure in a filtration unit	- Constant pressure of 5.8 bar for a flow rate of 1.08l/s - Proposal of a PS model detailed enough for simulations	Lack of irradiance and temperature profiles to better assess the performance of the proposed algorithm
[6]	Modelling of a PV PS and implementation of four algorithms (P&O-PI and Fuzzy-PI) optimized with genetic algorithms (GA) and particle swarm algorithms (PSO) to improve system efficiency	- Proposal for a functional model Development of an MPPT algorithm (Fuzzy-PI-PSO) that forces the system to supply water at very low irradiance (150 W/m2)	- Complex model with a heavy calculation load - The temperature is assumed to be constant during the simulations.
[7]	Comparative performance study between a PS equipped with a storage tank and a system equipped with a storage battery	- Storage tank systems require little or no maintenance, and have a very low environmental impact compared with battery systems - Systems with storage batteries have a lifecycle cost around 22.5% lower than systems with storage tanks	Systems with storage batteries have more pump on-off cycles (107 compared with 8), which is not good for the pump
[13]	Using the P&O algorithm to optimize power transfer	Proposal of an MPPT algorithm based on the P&O algorithm for controlling the inverter with a maximum efficiency of 92%	- The behavior of the system is only studied for two levels of irradiance - Carry out a financial study to assess the financial impact of this cell technology
[14]	Use of two controllers to optimize the pumping system (The first controller is used to control the system to reach its maximum using a robust MPPT control strategy based on the Kalman filter algorithm (KF- MPPT). The second controller is based on 12-sector direct torque control (DTC)	- Proposed comparative study between the performance of the proposed method and conventional P&O and conductance increment methods - The proposed control considerably reduces torque and flux ripple, as well as the total harmonic distortion of the stator currents, thereby increasing the amount of water pumped	The influence of temperature is not taken into account in this study
[16]	Summary of research work	- Update on the state of knowledge of solar pumping systems - Proposal for a PS architecture applied to irrigation integrating IoT with three operating modes	- The different PS architectures are not examined. - Techniques for improving the efficiency of PS are not examined - The influence of meteorological parameters is not assessed on the proposed system
[17]	Study of a photovoltaic PS equipped with a battery bank and development of ways of improving the system's efficiency	- The ability to pump water at any time. - Average increase of 10.85% on a sunny day The use of the battery avoids the influence of rapid changes in irradiant on the system, but also ensures more regular pumping	Using batteries in the system reduces overall efficiency
[18]	Comparative study of remote solar water PS, considering various factors such as site location, system size and performance, in several climate-sensitive regions of India. Highlighting the power balance of different sites in India	- Highlighting the strengths of the Theni region in India, with a system efficiency of 58.9%, a pump efficiency of 66.4% and a performance ratio of 51.5%, with an average annual solar radiation of 5.65 kWh/m2 compared with the other study areas. - Preparation of PS power balances for each study area	- PVsyst provides an overview of losses, but may need specific details on certain losses, particularly if they are not well documented or understood by designers - Extend the study to hybrid systems
[19]	Development of a three-phase inverter architecture with fewer controlled switches (exactly four) in order to reduce costs and losses	This inverter architecture significantly reduces energy losses due to switching	The performance of this new architecture has not been studied for irradiances below 500W/m2 The influence of temperature on system performance

Continue Table 1. Summary of work reviewed

[20]	Comparative study of two methods of operating solar systems, namely direct coupling and coupling with a DC-DC adapter, using a genetic algorithm	The genetic algorithm MPPT technique offers 98% efficiency in power transfer, compared with 50% for direct coupling. That's a difference of around 50%	- Complex MPPT algorithm that is difficult to implement. - The influence of temperature is not considered in this study
[21]	Development of an MPPT technique based on measuring the irradiance and temperature of the PV generator combined with the characteristics of the PV generator and the motor-pump unit	- My method gives high motor efficiency at low irradiance (85% at 100W/m²) An increase in the flow of pumped water of around 8.4%	- The method is complex to implement. - The performances of this technique are not compared with those obtained by other methods The behavior of the technique has not been studied under partial shade
[24]	Proposed of a sizing method to optimize the characteristics of each element of the basic chain over the life cycle of these components	- Highlighting the influence of total head on the system's life cycle - Demonstration that power loss decreases as head increases (from 5% to 0% over a range of 6 to 26m)	Experimental data profiles are not shown
[25]	Study and proposal for a variable frequency drive architecture applied to controlling the speed of the pump motor unit as a function of light intensity	- This device improves output currents by a percentage of 21.4% and 22.4% compared with fixed-frequency devices - This device returns around 92% of the MPP available to the load. The system consumes very little of its own energy	The simulations are based on a single cell; a larger-scale study would give a better idea of the performance and viability of the system
[26]	Use of a FLC to continue the MPPT and increase the amount of WP per day	- Proposed comparative study of the P&O algorithm and the FLC on the same system - The FLC offers improved stability, greater precision and a faster convergence time, which optimizes efficiency. by 3%	Preparation of a comparative study with other MPPT methods
[26]	The proposed method is based on indirect field-oriented control (IFOC), which consists of operating the motor at optimum flux while minimizing induction motor losses. Using the MPPT P&O algorithm	The proposed method reduces losses, and efficiency is increased by 12%, 2.5% and 5% under 375W/m2, 750W/m2 and the daily profile respectively	The influence of temperature is not considered
[27]	Performance evaluation of three MPPT algorithms - Neurofuzzy; - Incrementing conductance: - Pertub and observe	Highlighting the speed of convergence of the P&O algorithm compared with other methods	- The influence of temperature is not considered during the simulations - Irradiance is considered constant (1000 W/m2)
[28]	Proposal of a techno-economic optimization model to optimally determine the capacity of the components of a PV-WP system using a water storage tank based on reliability and cost	Proposal of an optimal sizing algorithm for a PV system	Technical and economic study between PV pumping systems and PS using other power sources diesel, petrol, etc...)
[29]	Performance analysis of different control techniques (flux vector control, inverter output frequency adjustment control and constant V/F control) applied to a PS under three different PV array configurations	- Development of a control algorithm to operate the system at very low irradiance (120 W/m2) - Proposal of a control method to help reduce the cost of the system (reduction of around 13% on the number of panels to be installed)	The influence of temperature is not considered during the simulations
[30]	Tracking of the MPP using FL with irradiance as input and comparison of the results of the implementation with a PID control	- Proposal of an algorithm with an approximate efficiency of 98% - Increase in the volume of water pumped per day by 1.87 m³	- The influence of temperature is not considered during the simulations - Optimize the rules base to improve system efficiency

Continue Table 1. Summary of work reviewed

[31]	Proposal for a MPPT algorithm based on a PID controller	-The proposed technique offers a response time that is 32.7% faster than that of a fuzzy controller, and this method allows 2.2% more water to be pumped than the fuzzy method - Good performance in partial shade	The performance of this technique has not been assessed in the case of very low irradiance (<200 W/m2) - The influence of temperature is not studied. The order model is not shown
[32]	Development of a new tracking algorithm to ensure that PV water PS operates at MP	- Simple implement control algorithm - Very accurate and robust MPPT	-The model uses expensive sensors (to measure irradiance, temperature, etc.). -Propose a comparative study between this MPPT technique and other techniques The algorithm is implemented on a very small PV generator (24Wp)
[33]	Comparative study between the P&O approach and InC on the improvement of PS performance	InC offers better response time and oscillation rate around the MPP (particularly under low irradiance) and better power extraction than the P&O method	The irradiance profiles are not shown to better appreciate the performance of the proposed algorithm
[34]	Use of InC and scalar control to improve the energy efficiency of the PS	- Reducing the number of sensors for system control - Performance rate of 99.8% in MPPT monitoring at an irradiance of 1000 W/m2	- The influence of temperature is not considered in this study - Although scalar control is simple, it is less precise than vector control, for example. - Draw up a comparative study between the control used in this work and other types of control
[35]	Comparative study of two PS structures, battery-powered and solar-powered, and proposal of a structure combining the two and offering better performance	Proposal for a solar PS for irrigation with battery storage and a water tank	Lack of comparative study between the proposed system and the systems presented in the literature
[36]	Development of a fuzzy logic MPPT algorithm using two inputs (the voltage and current generated by the PV field)	- Proposal for a MATLAB model of a PS equipped with an asynchronous cage motor and a centrifugal pump. - Very low system response time (around 16 ms) thanks to the MPPT algorithm	The influence of meteorological variations is not considered in this study (simulations are carried out at the STC)
[37]	Study of the impact of cooling on the payback period	- Highlighting the influence of the type of cooling (air, water) on the payback period - The use of water as a cooling fluid for the lower surface of the panels offers the best performance in the system studied, with a payback time of 7.3 years, a return on investment of 13.7% and an internal rate of return of 10.9%	- Increased installation costs. - Although it increases the system's energy efficiency by 1.4%, 7.7% and 1.01%, respectively, during hours of maximum sunlight, compared with PV-WPS without cooling, this technique can lead to cracking of the PV panels (thermal shock)
[38]	Development of a mathematical model to assess the performance of a PS based on the pump's power curve and the characteristics of the panels	Highlighting the influence of static height on the flow of water pumped, regardless of variations in irradiance	- The influence of temperature is not considered in this study. The MPPT technique used is not shown
[39]	Proposal for a MPPT algorithm based on the InC technique	- The proposed algorithm has a response time of 0.30s, compared with 0.39s for the conventional algorithm, representing a 23.1% improvement in search speed - Good search speed for MPPT in the event of rapid changes in irradiance, 33.3% faster than the conventional algorithm	- The influence of temperature is not studied - The increment step remains fixed
[40]	Combination of variable pitch InC for MPPT control and FL and coupled with direct torque control for controlling the induction motor driving the pump to improve the energy efficiency of a pumping system	- Simple algorithm to implement - Comparison of the performance of the proposed method with that of the variable-pitch P&O method - The variable step InC gives a harmonic distortion rate of 4.85% and a daily response time of 4.6 h, unlike the variable step P&O method which gives a rate of 9.59% and a daily response timeof 5.1 h	- The study does not consider low irradiances 200 w/m2 - The influence of temperature is neglected - Complex technique to implement

Continue Table 1. Summary of work reviewed

[41]	Use of adaptive neural networks to determine the factors limiting the performance of PS	Losses due to the solar generator having the greatest impact on the efficiency of the PS, unlike the pump motor unit.	The amount of training and model validation data is very small.
[42]	Increase solar panel conversion efficiency by cooling the top surface with a constant flow of water	Thanks to this optimization method, an increase of 15% in the power supplied by the panel has been achieved compared to systems without cooling	- Only viable for small systems - Although effective, this method is difficult to optimize due to the thickness of the cooling water, the quality of this water (which modifies the angle of incidence of the light rays on the panel and can even prevent them from being converted entirely) - The system is not self-contained because The pump that circulates the cooling water is supplied by another source
[43]	Comparative study of the P&O MPPT and InC methods (both variable step), then combination of the technique offering the best performance with the indirect vector control technique to optimize the pumping system and analysis of the results	- The variable step InC effectively reduces oscillations around the MPPT with a response time of 3.05s - The study shows that the combination of variable-step InC and indirect vector control offers the best performance - Fairly precise control (around 98%) of the speed setpoint	- The study does not consider low irradiances <200 w/m2 - The influence of temperature is neglected - The influence of the rapid change in irradiance is not included in this study
[44]	Improving the efficiency of PS by water jet cooling on panels	Increase in efficiency from 1 to 1.27%	- Very little variation in irradiance during the experiment. - A technique for increasing efficiency that can cause cracks in PV panels (thermal shock) - Implementing the technique is very expensive for large systems
[45]	Carrying out a study of the limiting parameters of PS applied to homes, with a view to providing indicators for the choice of system equipment	- Highlighting of 6 parameters limiting the efficiency of pumping systems - This study highlights the fact that temperature has very little influence on the overall efficiency of the system	Variations in the water level of the spring are not taken into account
[46]	Development of a technique for tracking the optimum efficiency point of a solar PS based on pump characteristics	The proposed method increases the efficiency of PS by 6.7%, depending on the pump used	Implementing this method requires a good understanding of the meteorological history of the installation site and of the system itself
[47]	Development of an optimal sizing method for PV PS	A surface area of 33.1m2 was obtained using the proposed method, compared with 93 m2 for a design without optimization	- No comparative study with other dimensioning methods or tools - This method is difficult to generalize as it only offers the best performance over the period for which the data was used for dimensioning
[48]	Proposal for a remote-control system for a PS applied to irrigation to optimize water consumption and increase system efficiency	Proposal for a system to monitor various PS parameters	The system can only be used on small systems (less than 100W)
[49]	Comparative study between a direct-coupled pumping system and a system with a Lithium-Ion storage battery	Using batteries extends the life of the motor by reducing starting cycles. Increase in the volume of water pumped per day	The use of batteries reduces the overall efficiency of the system because of the addition of other equipment.
[50]	Use of FL for MPPT control and tracking in PS	- The current and voltage generated by the inverter have fewer harmonics and are therefore of better quality. The FLC is robust and effective in the face of variations in the limiting parameters of the solar panels.	- It is important to compare this method with the neuro-fuzzy method. - Although generating a good quality of energy, it would be important to quantify the energy losses due to switching.
[51]	Use of the particle swarm optimization method coupled with direct control of the pump motor torque to optimize the amount of water produced by the system	- Proposal for a control of architecture with a low overshoot of less than 1%. Low harmonic distortion architecture, which means good quality energy transfer to the induction machine	- Mechanical performance is not shown - The influence of temperature is not considered in this study - Implementing this architecture with a synchronous motor could further improve current results - Complex technique to implement

From Table 1, there are three main methods used to increase the efficiency of water solar pumping systems:

3.1. Control and optimization methods

In this category, they have:

3.1.1. Proposed inverter architecture with less switchgear [21]:

- Loss Reduction: Significantly reduces energy losses due to switching.
- Performance Limitations: Performance not studied for irradiances below 500 W/m², limiting full understanding.

3.1.2. Multiple controllers and advanced algorithms

- Efficiency Improvement: Reduction in torque ripple and harmonic distortion by 4.85% [42].
- Water Volume: 8.4% increase in water pumped [23].
- Complexity: Methods are complex to implement and do not account for temperature effects and partial shading.

3.1.3. MPPT Algorithms Based on FL and PID [27, 28, 32, 33, 41]

- MPPT Efficiency: FL and PID algorithms offer up to 98% efficiency [32], with a response time 32.7% faster compared to fuzzy controllers [33].
- Water Volume: 2.2% more water pumped compared to fuzzy methods [33].
- Limitations: Temperature and irradiance variations are not considered; performance often studied at standard irradiance levels of 1000 W/m².

3.2. Comparison of architecture and configuration methods

These methods include:

3.2.1. Direct-Coupled vs. Battery-Storage Systems

- Energy Transfer Efficiency: Genetic algorithm MPPT systems show 98% efficiency compared to 50% for direct coupling [22].
- Water Volume: 10.85% increase in water pumped with battery storage systems [19].
- Overall Efficiency: Battery inclusion reduces overall system efficiency due to additional equipment [53].

3.2.2. Systems with and Without Cooling:

- Efficiency Increase: Water cooling boosts panel efficiency by 15% compared to systems without cooling [44].
- Costs: Increased installation costs and potential for thermal shock damage to panels.

3.3. Technical and economic optimization methods

3.3.1. Sizing and economic models

- Surface Optimization: Proposed sizing method yields a surface area of 33.1 m² compared to 93 m² without optimization [51].
- Cost-Efficiency Comparison: Techno-economic studies show a 22.5% lower lifecycle cost for battery systems compared to tank systems [7].

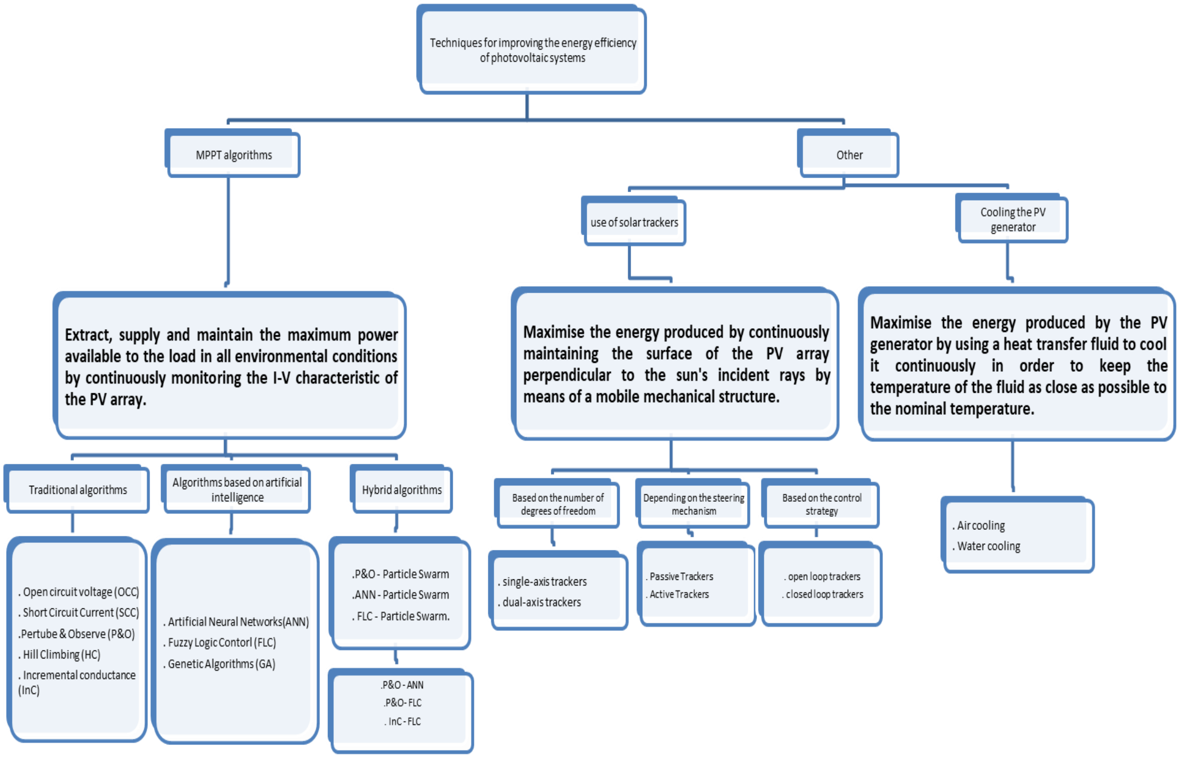
3.3.2. Techno-Economic Studies:

- Cost Reduction: Battery systems show a 22.5% reduction in lifecycle cost compared to storage tank systems [7].
- Low Irradiance Performance: The impact on performance at low irradiances (200 W/m²) is not thoroughly studied in several cases [35].

The studies reviewed offer various methods and technologies for optimizing photovoltaic (PV) water pumping systems, focusing on improving efficiency, reducing costs and enhancing system performance under different conditions. Many methods, such as MPPT algorithms using fuzzy logic, genetic algorithms and indirect field-oriented control, show promising results in increasing water yield and optimizing power transfer, with reported efficiency gains ranging from 3% to 98%. However, several limitations remain in these studies, including the lack of consideration of the influence of temperature, low irradiance conditions and partial shading, which are critical for real-world applications. In addition, the complexity and implementation challenges of some advanced techniques, such as Kalman filter-based MPPT or particle swarm optimization, are noted, highlighting the need for further comparative studies and practical validations to assess their viability on a larger scale. The studies also highlight the trade-offs associated with the use of battery storage, which, while beneficial for motor longevity and consistent pumping, tends to reduce overall system efficiency due to additional energy losses.

4. Techniques Used to Improve the Efficiency of Photovoltaic Systems, Particularly Pumping Systems

The various strategies for improving the energy efficiency of photovoltaic systems, particularly pumping systems (PS), are presented in this part of the work, providing a clear vision for new researchers in the field of optimizing these systems. The various strategies employed to improve the energy efficiency of photovoltaic. Fig. 9 shows the various strategies used to improve the energy efficiency of photovoltaic systems. The following sections (4.1, 4.2, 4.3 and 4.4) will provide a comprehensive overview of the techniques most commonly employed in pumping systems.



Extract, supply and maintain the maximum power available to the load in all environmental conditions by continuously monitoring the I-V characteristic of the PV array.

Maximise the energy produced by continuously maintaining the surface of the PV array perpendicular to the sun's incident rays by means of a mobile mechanical structure.

Maximise the energy produced by the PV generator by using a heat transfer fluid to cool it continuously in order to keep the temperature of the fluid as close as possible to the nominal temperature.

Fig. 9. Strategies for improving the energy efficiency of solar photovoltaic systems

4.1. Perturb & Observe (P&O) MPPT Algorithm

Among traditional algorithms, the Perturb and Observe algorithm is one of the most popular due to its simplicity of implementation. It works by perturbing the system voltage and observing the effect of this perturbation on the power output [52-57]. The operation of this technique is described by Fig. 10.

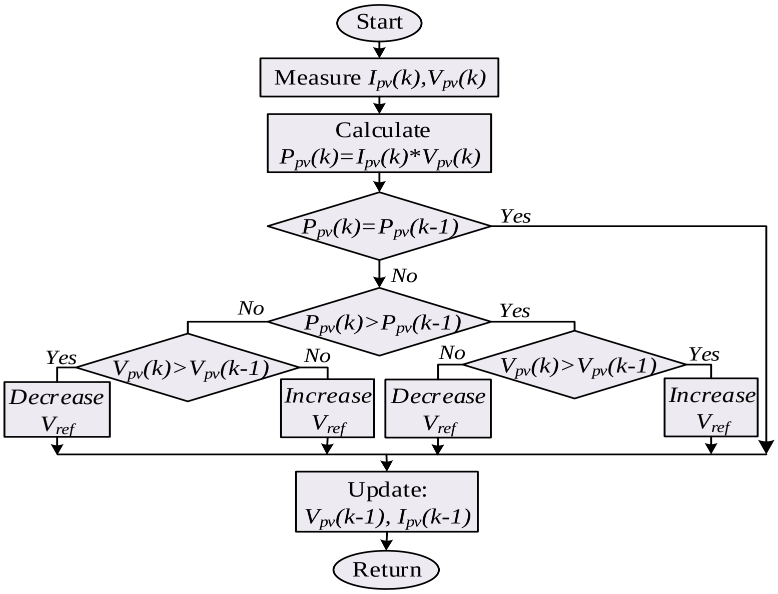


Fig. 10. Flowchart P&O [54]

The main advantages of this method are it’s easy to implement, requiring only two measurements (the voltage and current produced by the photovoltaic generator), and requires very few resources to deploy. What’s more, this method makes it possible to pinpoint the MPP even during variations in irradiance and temperature. Despite these considerable advantages, P&O control also has several limitations:

- Oscillations around the MPP generated steady-state operation due to the periodicity of the search process, forcing the system to oscillate constantly around this point.
- In the event of a rapid change in atmospheric conditions, such as the passage of a cloud, the response time of this control increases to reach the new MPP, thus generating energy losses [55].
- In the event of sudden variations in climatic conditions and/or load, this method can sometimes be misinterpreted in terms of the direction to follow to reach the MPP [55]. To alleviate this problem, [41, 42] propose a modified version of this algorithm to overcome the disadvantage of deviating from this method when searching for the MPP during rapid increases in irradiance and/or temperature levels.
- This control is difficult to optimize due to the choice of the disturbance variable, since a low increment value slows down the search for the MPP, and a high increment value would lead to high power losses in steady state.

4.2. MPPT algorithm conductance increment (InC)

The InC method flowchart explaining how to implement this method is illustrated in Fig. 11. This algorithm has been proposed to overcome the problems of several traditional algorithms. The main idea of this method is to compare the instantaneous conductance (Ipv/Vpv) and the incremental conductance (dIpv/dVpv) to determine the direction in which to adjust the voltage: the point of maximum power is reached when this derivative is zero. We can therefore write.

$$\frac{dPpv}{dVpv} = Ipv + Vpv\frac{\Delta Ipv}{\Delta Vpv} = 0 \rightarrow \frac{\Delta Ipv}{\Delta Vpv} = -\frac{Ipv}{Vpv} \tag{6}$$

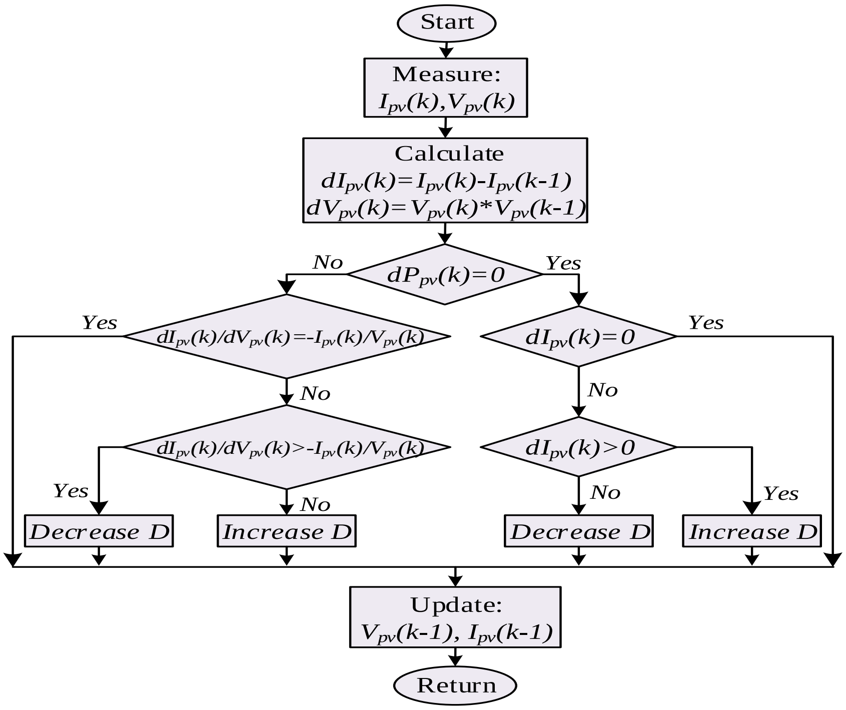


Fig. 11. Algorithm for tracking the MPP using the InC method [54]

To solve the problem of oscillation around the maximum power point (MPP), conductance increment control uses two conditions.

$$\frac{\Delta Ipv}{\Delta Vpv} = -\frac{Ipv}{Vpv} \; et \; \Delta Ipv = 0 \tag{7}$$

Eq. (7) allows the operating voltage to be kept constant when the MPP is reached; but this is only valid in theory, since in practice the condition.

$$\frac{\Delta Ipv}{\Delta Vpv} = -\frac{Ipv}{Vpv} \tag{8}$$

This condition is rarely true, which always results in small oscillations around MPP. Despite its major advantages, conductance increment control is a cumbersome method. Indeed, due to its complexity, this method requires a longer calculation time. As a result, detection of the MPP during rapid changes in weather conditions becomes difficult [11, 58].

4.3. Fuzzy logic MPPT algorithm

It is a method, enabling a set of decisions to be formulated in linguistic terms (whose values are words or natural expressions, such as: cold, hot, warm, very cold, fast, and slow. Large, medium, small. Max, min. Positive, null, negative, etc. ...). These linguistic terms use fuzzy sets to describe the magnitudes of the error, its variation and the appropriate control. Systems with non-precise and non-linear inputs can be treated with fuzzy logic [57, 58]. In fuzzy logic, the error (E) and the variation of the error (CE) are considered as inputs, while the variation of the reference voltage (duty cycle (dD)) will be considered as an output with:

$$E(n) = \frac{\Delta P}{\Delta V} = \frac{P(n)-P(n-1)}{V(n)-V(n-1)} \tag{9}$$

where P(n) and V(n) are the power and the voltage of the PV panel at time n.

and.

$$CE(n) = (E_n - E_{(n-1)}) \tag{10}$$

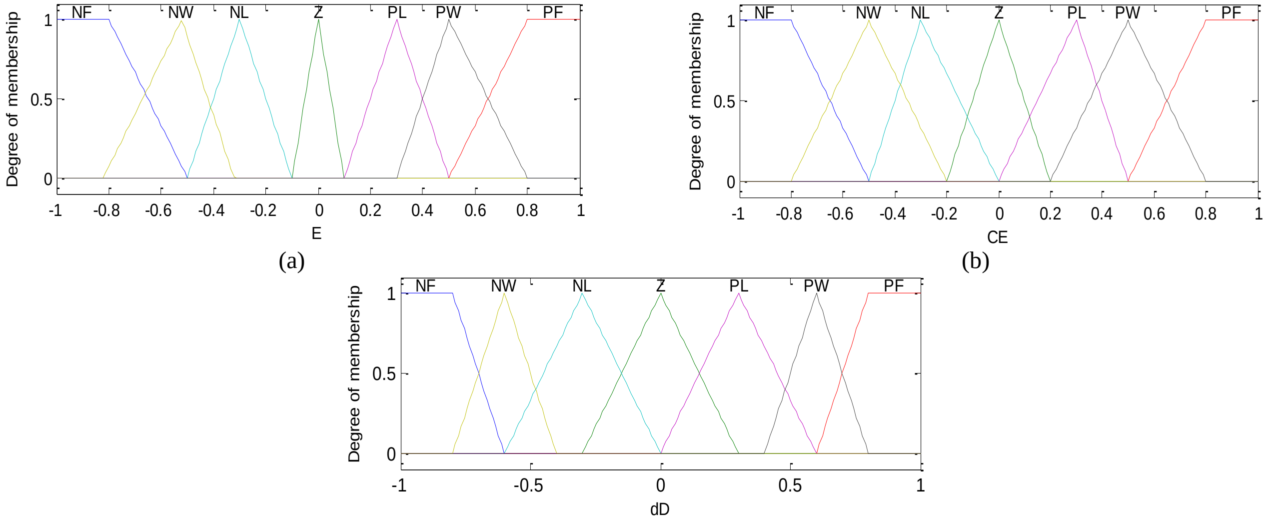
CE(n) is error change at time n, En and $E_{(n-1)}$ are respectively the error at time n and at time n-1.

Three mechanisms are required to implement a fuzzy controller:

Fuzzification: This first step involves determining the degree to which each input variable belongs to each state. In other words, fuzzification transforms real numerical input variables into fuzzy variables. These states are determined using the membership functions defined in the system.

Inference: is the process of working out the relationships between the input variables and the output variable.

Fig. 12 illustrates the fuzzy sets: (a) the input error the input error, (b) the input error change and (c) the output the output, which contains seven triangular membership functions.



(a)

(b)

(c)

Fig. 12. Membership functions; (a) for E(n), (b) for CE(n), and (c) for dD [54]

The relationships between the inputs (E(n), and CE(n)) and the output (dD) need to be defined. An example of a control rule from Table 2 is as follows:

Table 2. Rules of the Fuzzy System [54]

		CE						
		NF	NW	NW	Z	PL	PW	PF
	NF	NF	NF	NF	NW	NW	NL	Z
	NW	NF	NF	NW	NW	NL	Z	PL
	NL	NF	NM	NM	NL	Z	PL	PW
E	Z	NM	NM	NL	Z	PL	PW	PW
	PL	NM	NL	Z	PL	PW	PW	PF
	PW	NL	Z	PL	PW	PM	PF	PF
	PF	Z	PL	PW	PW	PF	PF	PF

Table 2 reads as follows: if E is NL and CE is NW, then D is NM.

Defuzzification: this stage consists of converting the fuzzy output subsets into a precise numerical value. The diagram of Fig. 13 provides an illustrated summary of these various stages.

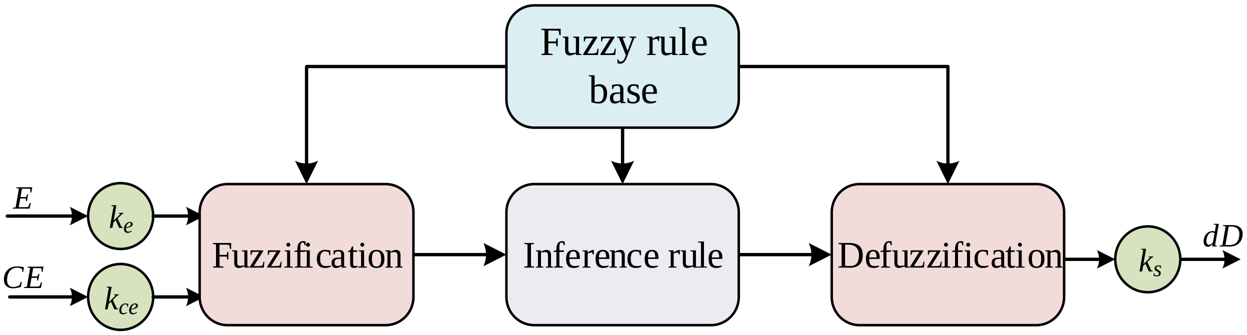


Fig. 13. Block diagram of a fuzzy controller [9]

FLC are becoming increasingly popular because of the evolution of microcontrollers. The advantage of these techniques is that they can operate with low-precision input values, and do not require high-precision mathematical models. In addition, they can handle nonlinearities [32, 54, 58]. However, their effectiveness depends very much on the knowledge of the user or control engineer in choosing the right error calculation and construction of the fuzzy system rule in Table 2. Deployment of this method is also complex.

4.4. PV generator cooling

To minimize the system costs of improving the energy efficiency of PWPS, air and water are the two heat transfer fluids generally used for cooling, as illustrated in Fig. 14. Indeed, these fluids are driven by a pump and are used in two modes each: air (respectively water) flowing over the upper surface of the PV generator, air (respectively water) flowing over the lower surface of the PV generator [37].

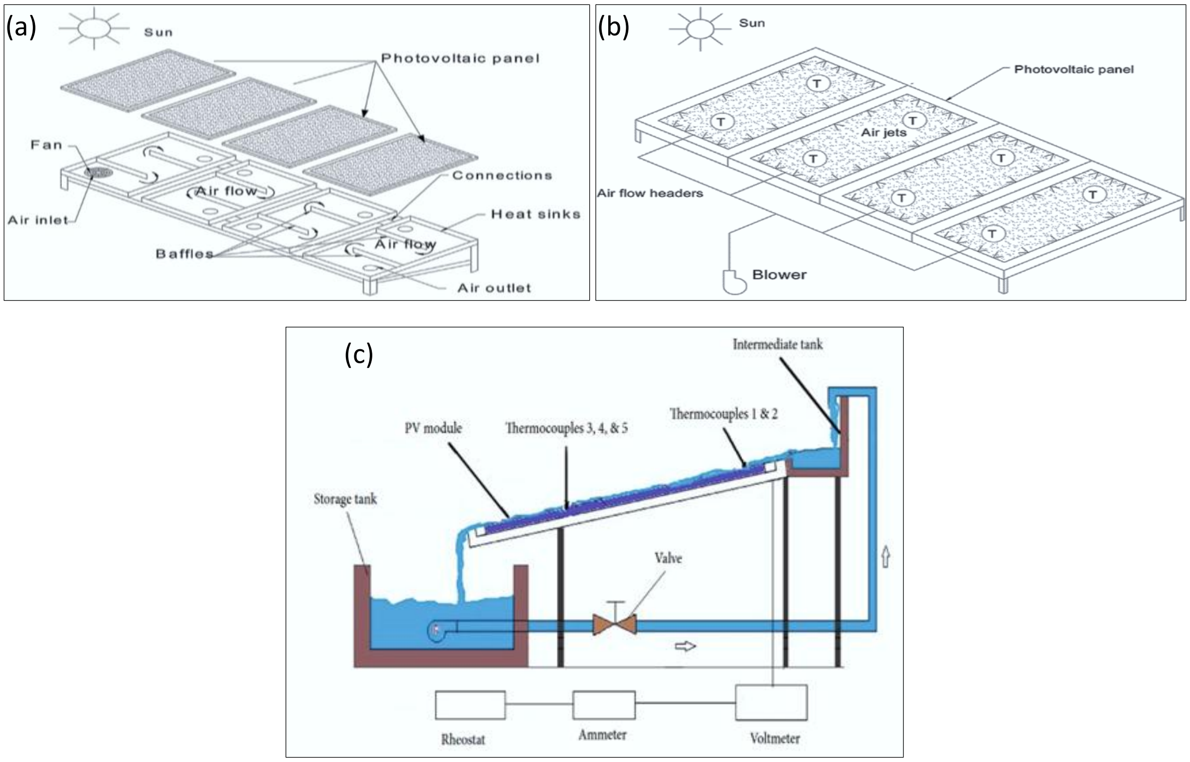


Fig. 14. Visual illustration of the different cooling modes: (a) Air cooling below solar panels [37], (b) Air cooling above solar panels [37], (c) Water cooling above solar panels [42]

This technique is particularly suitable for small systems; nevertheless, its limitations are not negligible: it can lead to cracks in PV panels, especially in systems using water spray cooling [44]; it is difficult to optimize due to factors such as the thickness and quality of the cooling water, which can alter the angle of incidence of light rays on the generator and even entirely prevent them from being converted when the water flows over the PV generator; implementing the technique is costly for large systems; and there is a need to use two pumps. Table 3 compares the performance of the different techniques presented above.

Table 3. Comparison of the most common methods used in photovoltaic pumping systems

Technique used	Measures required	Efficiency	Complexity	Search speed	implementation
Algorithm P&O	Ipv, Vpv	Medium	Low	Medium	Easy
Algorithm IC	Ipv, Vpv	Medium	Medium	Medium	Easy
Algorithm FLC	Ipv, Vpv	high	high	high	Medium

5. Conclusion

In this article, we have taken a close look at various works available in the literature on pumping systems. First, we reviewed the various components of PWPS - their components and functions. Then we focused on a critical analysis of several works available in the literature, notably those dealing with improving the efficiency of these systems. Finally, we looked at strategies for improving the efficiency of photovoltaic pumping systems. The overall efficiency of the system is the product of the efficiencies of each system component (photovoltaic (PV) generator, motor-pump unit, converters), which is reduced by the conversion efficiency of the solar panels and further reduced by unfavorable meteorological conditions (temperature and irradiance). However, many methods, such as MPPT algorithms using fuzzy logic, genetic algorithms, and indirect field-oriented control, show promising results in increasing water output and optimizing power transfer, with reported efficiency gains ranging from 3% to 98%. As a result, the efficiency of the PV generator must be optimal at all times to maintain the efficiency of the PS and extend its service life. For future work, it would be wise to consider:

- The use of a variable-step InC-FLC to extract maximum power at any time and especially under rapidly changing conditions.
- Consider the use of pumped water (which has the peculiarity of having a very low temperature) to cool and even clean the panels making up the PV generator mounted on a solar tracker.

Photovoltaic water pumping systems have great potential for supplying water in rural areas of Cameroon, particularly in its northern zone due to its geographical location and solar energy potential.

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Data Availability Statement

All data generated or analysed during this study are available from the corresponding author on reasonable request.

References

[1] Berahab, R. (2019). Energies renouvelables en Afrique : Enjeux, défis et opportunités. Policy Center for the New South : Rabat, Morocco.

[2] Periasamy, P., Jain, N. K., & Singh, I. P. (2015). A review on development of photovoltaic water pumping system. Renewable and Sustainable Energy Reviews, 43(2015), 918-925. https://doi.org/10.1016/j.rser.2014.11.019.

[3] Bentata, M., & Doudou, S. (2024, May). PSO-Enhanced Optimization of Sliding Mode Controller and Observer for a Photovoltaic Pumping System. In 2024 2nd International Conference on Electrical Engineering and Automatic Control (ICEEAC) (pp. 1-7). IEEE. https://doi.org/10.1109/iceeac61226.2024.10576474

[4] Bouchakour, A., Abdelhalim, B., Benbaha, N., Zaghba, L., Amor, F., Boukebbous, S. E., & Rabehi, A. (2024). Improving and evaluating the performance of a real photovoltaic pumping system for agricultural irrigation purposes in a desert environment at Ghardaia, Algeria. studies in engineering and exact sciences, 5, 418-431. https://doi.org/10.54021/seesv5n1-025.

[5] Boussaibo, A., Kamta, M., Kayem, J., Toader, D., Haragus, S., & Maghet, A. (2015). Characterization of photovoltaic pumping system model without battery storage by MATLAB/Simulink. IEEE (Eds.), 2015 9th International Symposium on Advanced Topics in Electrical Engineering (ATEE), 774-780. https://doi.org/10.1109/ATEE.2015.7133907.

[6] Bouchakour, A., Borni, A., & Brahami, M. (2021). Comparative study of P&O-PI and fuzzy-PI MPPT controllers and their optimisation using GA and PSO for photovoltaic water pumping systems. International Journal of Ambient Energy, 42(15), 1746-1757. https://doi.org/10.1080/01430750.2019.1614988.

[7] Soenen, C., Reinbold, V., Meunier, S., Cherni, J. A., Darga, A., Dessante, P., & Quéval, L. (2021). Comparison of Tank and Battery Storages for Photovoltaic Water Pumping. Energies, 14(9), 2483. https://doi.org/10.3390/en14092483.

[8] Dandoussou, A., Kamta, M., Bitjoka, L., Wira, P., & Kuitché, A. (2015). Simulations Based on Experimental Data of the Behaviour of a Monocrystalline Silicon Photovoltaic Module. Journal of Solar Energy, 2015(169015), 1-9. https://doi.org/10.1155/2015/169015.

[9] Nzoundja Fapi, C., Wira, P., Kamta, M., & Colicchio, B. (2021). Design and Hardware Realization of an Asymmetrical Fuzzy Logic-based MPPT Control for Photovoltaic Applications. IEEE (Eds.), 47th Annual Conference of the IEEE Industrial Electronics Society (IES). Toronto, Canada. https://doi.org/10.1109/IECON48115.2021.9589287.

[10] Baba, A. O., Liu, G., & Chen, X. (2020). Classification and Evaluation Review of Maximum Power Point Tracking Methods. Sustainable Futures, 2, 100020. https://doi.org/10.1016/j.sftr.2020.100020.

[11] Shang, L., Guo, H., & Zhu, W. (2020). An improved MPPT control strategy based on incremental conductance algorithm. Protection and Control of Modern Power Systems, 5(1), 14. https://doi.org/10.1186/s41601-020-00161-z.

[12] El Hammoumi, A., Chtita, S., Motahhir, S., & Abdelaziz, el ghzizal. (2022). Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar trackers and floating solar panels. Energy Reports, 8(2022), 11992-12010. https://doi.org/10.1016/j.egyr.2022.09.054.

[13] Zaky, A. A., Ibrahim, M. N., Rezk, H., Christopoulos, E., El Sehiemy, R. A., Hristoforou, E., Kladas, A., Sergeant, P., & Falaras, P. (2020). Energy efficiency improvement of water pumping system using synchronous reluctance motor fed by perovskite solar cells. International Journal of Energy Research, 44(14), 11629-11642. https://doi.org/10.1002/er.5788.

[14] Saady, I., Karim, M., Bossoufi, B., El Ouanjli, N., Motahhir, S., & Majout, B. (2023). Optimization and control of photovoltaic water pumping system using kalman filter based MPPT and multilevel inverter fed DTC-IM. Results in Engineering, 17(2023), 100829. https://doi.org/10.1016/j.rineng.2022.100829.

[15] Tan, S. C., & Tse, C. K. (2012). Converter topologies. In Dynamics and Control of Switched Electronic Systems: Advanced Perspectives for Modeling, Simulation and Control of Power Converters (pp. 3-24). London : Springer London. https://doi.org/10.1007/978-1-4471-2885-4_1

[16] Singh, D. B., Mahajan, A., Devli, D., Bharti, K., Kandari, S., & Mittal, G. (2021). A mini review on solar energy based pumping system for irrigation. Materials Today: Proceedings, 43(2021), 417-425. https://doi.org/10.1016/j.matpr.2020.11.716.

[17] Garrido-Sarasol, J.-Á., Orts-Grau, S., Gasque, M., González-Altozano, P., Balbastre-Peralta, I., Gimeno-Sales, F.-J., & Segui-Chilet, S. (2024). Technical performance analysis of high-voltage battery-based photovoltaic water pumping systems. Energy Conversion and Management, 22 (2024), 100543. https://doi.org/10.1016/j.ecmx.2024.100543.

[18] Pachaivannan, P., Manimuthu, S., & Jegadeesan, V. (2024). Comparative energy performance analysis of solar water pumping systems across diverse climate zones. Journal of Engineering Research. https://doi.org/10.1016/j.jer.2024.03.011.

[19] Narendra, A., Venkataramana, N. N., Panda, A. K., Tiwary, N., & Kumar, A. (2022). A Single-Stage SPV-Fed Reduced Switching Inverter-Based Sensorless Speed Control of IM for Water Pumping Applications. International Transactions on Electrical Energy Systems, 2022(380579), 12. https://doi.org/10.1155/2022/3805791.

[20] Hilali, A., Mardoude, Y., Essahlaoui, A., Rahali, A., & Ouanjli, N. E. (2022). Migration to solar water pump system: Environmental and economic benefits and their optimization using genetic algorithm Based MPPT. Energy Reports, 8(2022), 10144-10153. https://doi.org/10.1016/j.egyr.2022.08.017.

[21] Altimania, M., Elsonbaty, N., Enany, M., Gamil, M., Alzahrani, S., Alraddadi, M., Alsulami, R., Alhartomi, M., Alghuson, M., Alatawi, F., & Mossad, M. I. (2023). Optimal Performance of Photovoltaic-Powered Water Pumping System, 11(731),1-21 https://doi.org/10.3390/math11030731.

[22] Sontake, V. C., & Kalamkar, V. R. (2016). Solar photovoltaic water pumping system-A comprehensive review. Renewable and Sustainable Energy Reviews, 59(2016), 1038-1067. https://doi.org/10.1016/j.rser.2016.01.021.

[23] Shutterstock (2024). photos de stock, objets 3D et images vectorielles. (s. d.). received from https://www.shutterstock.com/fr/search/surface-pump

[24] Bakelli, Y., Hadj Arab, A., & Azoui, B. (2011). Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept. Solar Energy, 85(2), 288-294. https://doi.org/10.1016/j.solener.2010.11.023.

[25] Kim, J. H., Byeon, S. D., Mo, H.-S., & Min, K.-S. (2014). Reconfigurable Charge Pump Circuit with Variable Pumping Frequency Scheme for Harvesting Solar Energy under Various Sunlight Intensities. International Journal of Photoenergy, 2014(437641), 9. https://doi.org/10.1155/2014/437641.

[26] Errouha, M., Derouich, A., El Ouanjli, N., & Motahhir, S. (2020). High-Performance Standalone Photovoltaic Water Pumping System Using Induction Motor. International Journal of Photoenergy, 2020(3872529), 13. https://doi.org/10.1155/2020/3872529.

[27] Yahyaoui, I., Nafaa, J., Charfi, S., Chaabene, M., & Tadeo, F. (2015). MPPT techniques for a photovoltaic pumping system. IEEE (Eds.), The 6th International Renewable Energy Congress (1-6). https://doi.org/10.1109/IREC.2015.7110905.

[28] Olcan, C. (2015). Multi-objective analytical model for optimal sizing of stand-alone photovoltaic water pumping systems. Energy Conversion and Management, 100(2015), 358-369. https://doi.org/10.1016/j.enconman.2015.05.018.

[29] Yaichi, M., Fellah, M.-K., Mammeri, A., Tayebi, A., & Abdelkader, B. (2016, octobre 25). Contrôle et Analyse des Performances d'un Système de Pompage Photovoltaïque. The 4th International Seminar on New and Renewable Energies(1-7).

[30] Maranhao, G. N. A., Brito, A. U., Pinho, J. T., Fonseca, J. K. S., Leal, A. M., & Macedo, W. N. (2016). Experimental Results of a Fuzzy Controlled Variable-Speed Drive for Photovoltaic Pumping Systems : A Review. IEEE Sensors Journal, 16(9), 2854-2864. https://doi.org/10.1109/JSEN.2016.2524530.

[31] Fawzy El-Khatib, M., Shaaban, S., & Abu El-Sebah, M. I. (2017). A proposed advanced maximum power point tracking control for a photovoltaic-solar pump system. Solar Energy, 158(2017), 321-331. https://doi.org/10.1016/j.solener.2017.09.051.

[32] Enany, M. A. (2017). Cuckoo search–based maximum power point tracking controller for PV water pumping system. Journal of Renewable and Sustainable Energy, 9(6), 063501. https://doi.org/10.1063/1.5009681.

[33] Harrag, F. A., Titraoui, S. A., & Bahri, T. H. (2017). P&O or IC for PV pumping system : What MPPT algorithm to improve performances?. IEEE (Eds.), 2017 6th International Conference on Systems and Control (ICSC) (220-225). Batna, Algeria https://doi.org/10.1109/ICoSC.2017.7958724.

[34] Singh, B., Sharma, U., & Kumar, S. (2018). Standalone Photovoltaic Water Pumping System Using Induction Motor Drive With Reduced Sensors. IEEE Transactions on Industry Applications, 54(4), 3645-3655. https://doi.org/10.1109/TIA.2018.2825285.

[35] Biswas, S., & Iqbal, M. T. (2018). Dynamic Modelling of a Solar Water Pumping System with Energy Storage. Journal of Solar Energy, 2018(8471715),12. https://doi.org/10.1155/2018/8471715.

[36] Ksentini, A., Azzag, E., & Bensalem, A. (2019). Sizing and optimisation of a photovoltaic pumping system. International Journal of Energy Technology and Policy, 15 (1), 71-85. https://doi.org/10.1504/IJETP.2019.10017133.

[37] Mohanraj, M., P., C., M., S., & Kamaruzzaman, S. (2019). Performance of photovoltaic water pumping systems under the influence of panel cooling. Renewable Energy Focus, 31(00), 31-44. https://doi.org/10.1016/j.ref.2019.10.006.

[38] Salilih, E. M., Birhane, Y. T., & Arshi, S. H. (2020). Performance analysis of DC type variable speed solar pumping system under various pumping heads. Solar Energy, 208, 1039-1047. https://doi.org/10.1016/j.solener.2020.08.071.

[39] Sarfo, K., Amuna, W., Pouliwe, B., & Effah, F. (2020). An Improved P&O MPPT Algorithm Under Partial Shading Conditions. IEEE (Eds.), ,(1-5). Nairobi, Kenya: IEEE.https://doi.org/10.1109/PowerAfrica49420.2020.9219851.

[40] Errouha, M., Derouich, A., Nahid-Mobarakeh, B., Motahhir, S., & El Ghzizal, A. (2019). Improvement control of photovoltaic based water pumping system without energy storage. Solar Energy, 190(2019), 319-328. https://doi.org/10.1016/j.solener.2019.08.024.

[41] Statkic, S., Jovanovic, B., Micic, A., Arsic, N., & Jović, S. (2020). Adaptive neuro fuzzy selection of the most important factors for photovoltaic pumping system performance prediction. Journal of Building Engineering, 30, 101242. https://doi.org/10.1016/j.jobe.2020.101242.

[42] Govardhanan, M. S., Kumaraguruparan, G., Kameswari, M., Saravanan, R., Vivar, M., & Srithar, K. (2020). Photovoltaic Module with Uniform Water Flow on Top Surface. International Journal of Photoenergy, 2020(8473253), 9. https://doi.org/10.1155/2020/8473253.

[43] Saady, I., Karim, M., Bossoufi, B., Motahhir, S., Adouairi, M. said, Majout, B., Lamnadi, M., Masud, M., & Al-Amri, J. F. (2021). Optimization for a Photovoltaic Pumping System Using Indirect Field Oriented Control of Induction Motor. Electronics, 10(24), 3076. https://doi.org/10.3390/electronics10243076.

[44] Ashok Kumar, L., Indragandhi, V., Teekaraman, Y., Kuppusamy, R., & Radhakrishnan, A. (2022). Design and Implementation of Automatic Water Spraying System for Solar Photovoltaic Module. Mathematical Problems in Engineering, 2022, 7129610. https://doi.org/10.1155/2022/7129610.

[45] Meunier, S., Loic, Q., Darga, A., Dessante, P., Marchand, C., Matthias, H., Cherni, J., de La Fresnaye, E., Vido, L., Multon, B., & Kitanidis, P. (2020). Sensitivity Analysis of Photovoltaic Pumping Systems for Domestic Water Supply. IEEE Transactions on Industry Applications, 56, 6734-6743. https://doi.org/10.1109/TIA.2020.3013513.

[46] Sena Dos Santos, W., Ferreira Torres, P., Ubaiara Brito, A., Arrifano Manito, A. R., Figueiredo Pinto Filho, G., Leão Monteiro, W., & Negrão Macêdo, W. (2021). A novel method to determine the optimal operating point for centrifugal pumps applied in photovoltaic pumping systems. Solar Energy, 221(2021), 46-59. https://doi.org/10.1016/j.solener.2021.04.005.

[47] Hafian, A., Benbrahim, M., & Kabbaj, M. (2022). A novel algorithm for optimal sizing of stand-alone photovoltaic pumping systems. International Journal of Power Electronics and Drive Systems, 13(3), 1833-1842. https://doi.org/10.11591/ijpeds.v13.i3.pp1833-1842.

[48] Harkani, A., CHAHIM, NABOULSI, & Abdellah, E. A. (2022). Standalone Photovoltaic Water Pumping System Directly Coupled and Controlled by IoT Technologies. https://doi.org/10.13140/RG.2.2.22484.07045.

[49] Gasque, M., González-Altozano, P., Gimeno-Sales, F. J., Orts-Grau, S., Balbastre-Peralta, I., Martínez-Navarro, G., & Segui-Chilet, S. (2022). Energy Efficiency Optimization in Battery-Based Photovoltaic Pumping Schemes. IEEE Access, 10, 54064-54078. https://doi.org/10.1109/ACCESS.2022.3175586.

[50] Aouzellag, D., Amirouche, E., Berboucha, A., Ghedamsi, K., Dermouni, K., & Aissou, S. (2024, janvier 10). Fuzzy Logic Control of a Photovoltaic Water pumping System. The 1st national conference on emergent technologies in electrical engineering (NCETEE'23), 1. Setif, Algeria.

[51] Abdelilah, H., Makhad, M., El marghichi, M., Ouanjli, N. E., & Loulijat, A. (2024). Towards sustainable water pumping systems: Integration of particle swarm optimization and direct torque control PSO-DTC. e-Prime - Advances in Electrical Engineering, Electronics and Energy, 7, 10144-10153. https://doi.org/10.1016/j.prime.2024.100480.

[52] Salman, S., Ai, X., & Wu, Z. (2018). Design of a P-&-O algorithm based MPPT charge controller for a stand-alone 200W PV system. Protection and Control of Modern Power Systems, 3(1), 25. https://doi.org/10.1186/s41601-018-0099-8.

[53] Ahmed, J., & Salam, Z. (2018). An Enhanced Adaptive P&O MPPT for Fast and Efficient Tracking Under Varying Environmental Conditions. IEEE Transactions on Sustainable Energy, 13(1), 1-17. https://doi.org/10.1109/TSTE.2018.2791968.

[54] Nzoundja Fapi, C., Kamta, M., & Wira, P. (2019). A comprehensive assessment of MPPT algorithms to optimal power extraction of a PV panel. Journal of Solar Energy Research 4(3), 172-179. https://doi.org/10.22059/jser.2019.287029.1126.

[55] Sera, D., Kerekes, T., Teodorescu, R., & Blaabjerg, F. (2006). Improved MPPT Algorithms for Rapidly Changing Environmental Conditions. EPE-PEMC 2006: 12th International Power Electronics and Motion Control Conference (1614-1619).Portoroz,solvenia: https://doi.org/10.1109/EPEPEMC.2006.4778635.

[56] Anowar, M. H., & Roy, P. (2019). A Modified Incremental Conductance Based Photovoltaic MPPT Charge Controller. IEEE (Eds.), 2019 International Conference on Electrical Computer and Communication Engineering (ECCE), 1-5. Cox'sBazar, Bangladesh https://doi.org/10.1109/ECACE.2019.8679308.

[57] Selvaraj, S., Veerasamy, M., R., D., Muthukumarasamy, N., Thiyagarajan, S., Thanikanti, S. B., & N., P. (2023). A review on mppt algorithms for solar pv systems. International Journal of Research -granthaalayah, 11(3), 25-64. https://doi.org/10.29121/granthaalayah.v11.i3.2023.5086.

[58] Nzoundja Fapi, C., Wira, P., Kamta, M., Tchakounte, H., & Colicchio, B. (2021). Simulation and dSPACE Hardware Implementation of an Improved Fractional Short-Circuit Current MPPT Algorithm for Photovoltaic System. Applied Solar Energy, 57(2), 93-106. https://doi.org/10.3103/S0003701X21020080.