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Experimental and Simulated Analysis of Cloud Passage Effects on a Solar-Tracked Stand-Alone PV Water Pumping System

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Abstract. This paper presents an in-depth analysis and simulation of the effects produced by cloud passages on the operation of a stand-alone direct photovoltaic (PV) water pumping system. The study is based on a long-term experimental dataset collected at an isolated PV installation in Cariñena (Spain), specifically designed for agricultural irrigation. Cloud events were classified into three main types -cloud trains, compact clouds, and isolated cloud events- and their statistical occurrence and impact on system performance were evaluated across different seasons. A data-logger was developed to monitor key electrical and environmental parameters with high temporal resolution, enabling the identification and quantification of transient effects associated with sudden irradiance drops. The most critical situation arises during sequences of cloud trains, where frequent restarts and short operating cycles reduce the overall efficiency and increase mechanical stress. A simulation model was implemented to reproduce the dynamic behaviour of the system during cloud events, validating the experimental results and offering predictive capabilities for performance estimation. The novelty of the approach lies in the integration of cloud passage statistics with real-time performance analysis, allowing for a deeper understanding of the mismatch between energy generation and hydraulic demand. The study also highlights the advantages of direct PV pumping systems, such as simplicity, low maintenance, and cost-effectiveness, while highlighting their limitations under unstable weather conditions.

Keywords. Cloud Passage, Photovoltaic Water Pumping System, Cloud Trains, Compact Cloud, partial shading, performance degradation.

1. Introduction

Stand-alone photovoltaic water pumping systems have emerged as a sustainable and economically viable alternative to traditional diesel or grid-connected pumping solutions, particularly in rural and remote regions. These systems operate without the need for batteries [1], offering significant advantages such as low maintenance, zero fuel consumption, and the absence of greenhouse gas emissions, noise, and air pollution. Recent studies [2] have confirmed their high reliability and cost-effectiveness in applications for domestic use, livestock, and agricultural irrigation. In fact, the operational and replacement costs of diesel-based systems can be two to four times higher than those of solar-powered systems. Depending on the context, hybrid configurations may further enhance performance and economic feasibility.

Several research efforts have analyzed the technological advances [3], optimization strategies [4], and limitations of direct PV water pumping systems [5], with particular focus on Maximum Power Point Tracking (MPPT) algorithms, system sizing, and control strategies [6]. However, one of the less studied yet critical issues is the impact of solar irradiance variability caused by cloud passages. Sudden reductions in solar input may cause system instability, efficiency losses, and interruptions in water supply, especially in systems without energy storage [7]. This study aims to address that gap by analyzing the influence of cloud transits on a real-world stand-alone PV water pumping installation equipped with a solar tracker. Through long-term data collection and simulation, the dynamic behaviour of the system is evaluated to assess its performance and propose improvement strategies under unstable weather conditions.

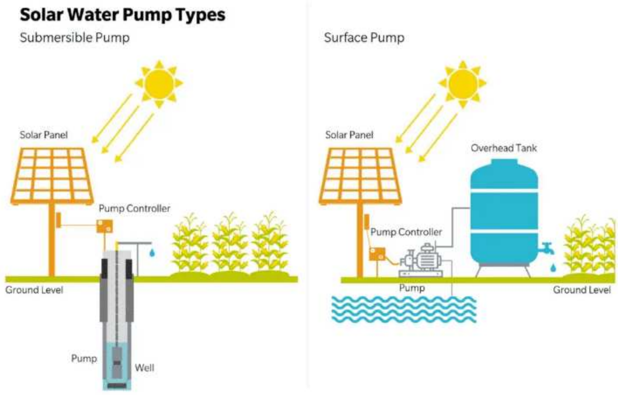

Fig. 1. Typical solar photovoltaic water pumping installations for irrigation and farms.

2. Cloud Passage Effects

The passage of clouds is one of the main sources of short-term solar irradiance variability, introducing transient fluctuations that significantly impact the performance of photovoltaic systems. In stand-alone photovoltaic water pumping systems, which are often deployed in remote or off-grid locations, these fluctuations can lead to abrupt changes in the power supplied to the pump, directly affecting the water flow rate and overall system reliability. Unlike grid-connected systems, stand-alone configurations lack external energy support, making them especially vulnerable to the stochastic nature of cloud movements.

Cloud passages can cause rapid and frequent changes in irradiance, sometimes reducing the input energy by more than 80% within seconds. These sudden dips in solar radiation can interrupt the operation of the pump or reduce its efficiency, as the available power may fall below the minimum threshold required for motor activation. In centrifugal pumps, which are typically used in these systems due to their simplicity and low cost, the relationship between power and flow is non-linear. Therefore, even small reductions in power can lead to disproportionately large decreases in water output. This situation becomes particularly critical during peak water demand periods, such as in agriculture or livestock management.

In addition to reducing power, cloud-induced fluctuations can introduce electrical and mechanical stress on system components. Frequent start-stop cycles caused by intermittent irradiance increase wear on the pump motor and control, potentially reducing their operational lifespan. Moreover, if the system includes a battery or ultra-capacitors for energy buffering, cloud transients can accelerate degradation due to continuous charge-discharge cycles under fluctuating conditions. The overall system efficiency is thus compromised not only by energy losses but also by increased maintenance requirements and potential downtimes.

Additionally, repeated transitions between irradiance levels can create problems for the maximum power point tracking (MPPT) algorithms. Many conventional MPPT controllers struggle to adapt quickly enough to rapid changes, resulting in further energy mismatches and suboptimal operation.

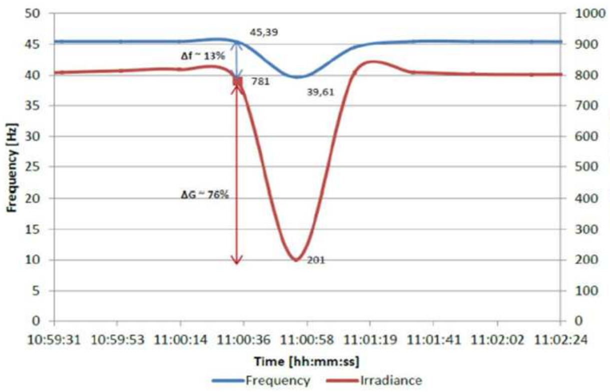

Fig. 2. Variation in the irradiance and frequency of the water pump during the passage of a cloud in a stand-alone photovoltaic water pumping system.

Modeling the effects of cloud passage is therefore essential for accurate performance prediction and system design. It requires not only high-resolution irradiance data but also dynamic simulation tools that can replicate short-term behaviour. Empirical studies have shown that systems operating under highly variable irradiance conditions exhibit lower average daily outputs compared to those under more stable skies, even if total daily irradiation is similar. This highlights the importance of temporal resolution in PV-system assessment.

In water pumping applications, mitigation strategies include the use of storage tanks with sufficient capacity to buffer short-term interruptions in flow, as well as integrating energy storage or hybrid power systems. However, these solutions increase system complexity and cost. A deeper understanding of cloud passage dynamics allows for more efficient sizing of PV-arrays and pumps, potentially reducing the need for oversizing and improving the economic viability of such installations.

In summary, cloud passage introduces complex and multi-layered effects on the energy availability and mechanical operation of stand-alone photovoltaic water pumping systems. Accurately quantifying and modeling these effects is crucial for designing robust, efficient, and long-lasting systems capable of delivering reliable water supply under fluctuating environmental conditions.

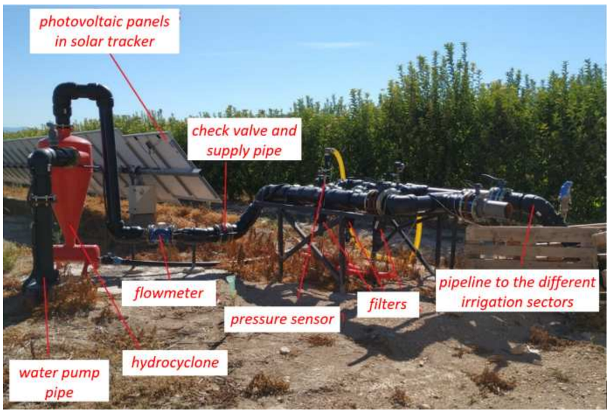

Fig. 3. Direct photovoltaic irrigation system subject to analysis and experimental validation. The photovoltaic water pumping system is composed of several components.

During the cloud passage, solar irradiance can experience a sudden decline—often dropping to approximately 75% of its initial value within just a few seconds—resulting in an immediate reduction in the power output of the photovoltaic system. A common phenomenon known as "cloud trains", characterized by successive short-duration clouds, can cause irradiance levels to fluctuate for several seconds or even minutes. Under such conditions, the irradiance received by PV-modules can fall from values around 800W/m² to 400W/m², or even as low as 200W/m², depending on cloud density and coverage. This intermittent pattern of alternating sunlight and shading produces significant variability in the energy supplied to the system.

The percentage of power losses (P_{Loss}) due to cloud-induced shading in a solar photovoltaic system can be quantified using the expression:

$$P_{Loss} = \frac{P_N - P_{MPPT}}{P_{MPPT}} \times 100\ (\%) \qquad (1)$$

where P_N represents the power output under partial shading conditions, and P_{MPPT} denotes the maximum power output under ideal irradiance (without shading).

In order to mitigate the adverse effects of cloud passages in direct-drive photovoltaic water pumping systems, a commonly applied control strategy is the dynamic adjustment of the pump's operating frequency. By reducing the frequency, the system lowers the water flow rate and consequently the energy demand, which helps to avoid complete system shutdowns during transient drops in irradiance. This adaptive response ensures that the system continues operating at a reduced capacity, allowing it to overcome short-term irradiance fluctuations without interruptions in water supply.

Fig. 4. Installation of smart photovoltaic panels in a vineyard. An example of how renewable energy generation coexists with the rural environment.

Fig. 5. Installation of smart photovoltaic panels in a vineyard. An example of how renewable energy generation coexists with the rural environment.

3. Mechanical and Hydraulic restrictions.

Fluctuations in solar irradiance caused by cloud passage have a direct and immediate impact on the energy available for PV-powered direct-drive water pumping systems. On cloudy days, the rapid alternation between irradiated and shaded conditions results in highly variable power supply to the pump motor. This variability is transmitted almost instantaneously to the hydraulic circuit, manifesting as abrupt variations in flow rate *Q(t)* and system pressure *P(t)*. In direct pumping configurations, which lack intermediate energy storage or regulation stages, these transient fluctuations introduce significant mechanical stress on the system in real time.

The dynamic behaviour of the hydraulic network under these conditions can be characterized by the unsteady flow equations. When the power supplied to the pump varies rapidly due to irradiance fluctuations, the pump head *H(t)* (remember that pump's head is the maximum height that the pump can achieve pumping against gravity) and flow rate *Q(t)* experience corresponding variations governed by the pump performance curves:

$$H(t) = aQ(t)^2 + bQ(t) + c \tag{2}$$

where *a*, *b*, and *c* are coefficients that depend on the specific pump geometry and operational parameters (data and information provided by the manufacturer). Sudden changes in *Q(t)* can result in pressure transients in the pipeline, which propagate at the wave speed a_w, typically described by the water hammer equation:

$$\Delta P = \rho a_w \Delta v \tag{3}$$

Here, ΔP is the pressure surge, ρ the fluid density (in the case of water ρ_w = 0,998 g/cm^3), a_w the wave speed in the pipeline (dependent on pipe elasticity and fluid compressibility), and Δv the change in fluid velocity. These pressure surges can reach several bars, enough to damage valves, joints, and other vulnerable components of the hydraulic system.

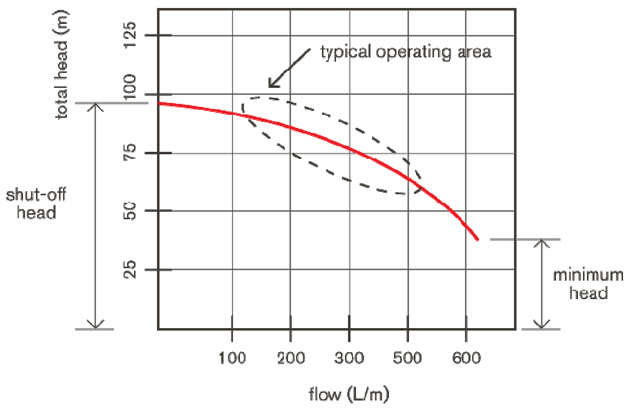

Fig. 6. Typical pump performance curve of total head versus flow rate.

Additionally, rapid decreases in pressure caused by insufficient pump power during irradiance drops can induce cavitation. This occurs when the local pressure *P* at the pump inlet falls below the water vapor pressure *Pv*:

$$P < Pv \rightarrow Cavitation \tag{4}$$

The implosion of vapor bubbles generates microjets and shockwaves that erode the pump impeller and surrounding materials. Repeated cavitation events degrade pump efficiency and lead to premature failure.

To avoid these mechanical instabilities, a viable strategy is to decouple the energy generation from the water delivery process by integrating a storage reservoir (irrigation pond or water tank). In this configuration, water is pumped into a tank during periods of adequate irradiance, and later distributed according to demand, independent of real-time solar conditions. This buffering process can be represented through a mass balance equation:

$$\frac{dV_s}{dt} = Q_{in}(t) - Q_{out}(t) \quad (5)$$

where V_s is the volume of stored water, $Q_{in}(t)$ the inflow rate from the pump (variable with solar input), and $Q_{out}(t)$ the controlled outflow rate to the irrigation system. By regulating $Q_{out}(t)$, it is possible to maintain a stable hydraulic output, reduce mechanical stress, and enhance the overall reliability and lifespan of the system.

Figures 7 and 8 show the impact of a cloud passage on a direct pumping photovoltaic system, as well as the evolution of the different variables. In this way, it is possible to observe how cloud passage events generate electrical and hydraulic instability.

- Irradiance (orange line) drops sharply at 60 seconds due to the passage of a cloud.
- Photovoltaic power (dashed red line) follows the same trend.
- The transient pressure *ΔP* (dotted purple line) represents the effect of water hammer during rapid flow changes.
- The flow rate (blue line) decreases during the irradiance drop, simulating the hydraulic system's response. It represents how the hydraulic system responds to the power drop.
- The hydraulic pressure in the system (green line) varies with the flow rate, showing a temporary drop.

Dynamic effects induced by cloud passage introduce complex mechanical constraints on direct-drive photovoltaic water pumping systems, including water hammer and cavitation. These phenomena can be analytically described and mitigated through appropriate system design strategies such as hydraulic decoupling and storage buffering, which not only preserve system integrity but also improve operational efficiency under variable solar conditions.

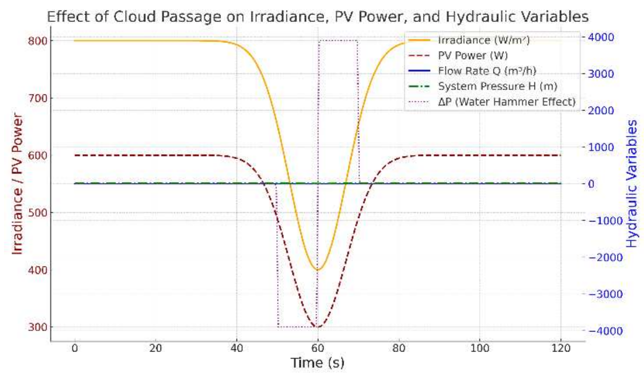

Fig. 7. Effect of cloud passage on irradiance, photovoltaic power and hydraulic variables. Water hammer phenomenon.

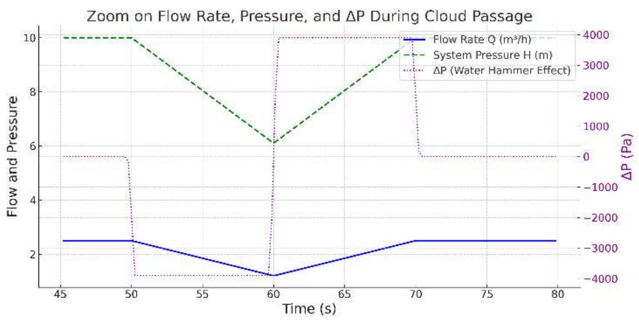

Fig. 8. Enlarged detail of the graph between seconds 45 and 80, just when the cloud passes.

4. Cloud passage data-logger.

To observe, analyze, and characterize the transient effects produced by cloud passage in a photovoltaic water pumping system, a data acquisition system (data-logger) was installed at the experimental facility. This system was configured to record data from the weather station, including ambient temperature, wind speed, and atmospheric pressure, alongside the solar irradiance and real-time photovoltaic power supplied by the solar panels. The experimental setup is located in Cariñena (Zaragoza, Spain) and is dedicated to vineyard irrigation using a direct photovoltaic water pumping system, with no intermediate energy storage.

A sampling frequency of 1Hz was chosen for the data-logger, enabling high temporal resolution and accurate tracking of fast-changing conditions, such as those induced by transient cloud events. From the 1-second data samples, minute-by-minute statistical indicators were computed for each variable: average, maximum, and minimum values. This approach allows for detecting both long-term patterns and short-lived fluctuations associated with cloud dynamics.

Two types of cloud formations were studied in detail: cloud trains, defined as sequences of rapidly successive clouds causing extended periods of shading; and compact clouds, which are dense, uniform and isolated cloud structures with more localized effects. These cloud types were classified and analyzed based on their duration and frequency over a three-year monitoring period (2019–2021). The results are summarized in Tables I and II.

TABLE I. ANNUAL STATISTICAL STUDY ASSOCIATED WITH CLOUD TRAINS IN A DIRECT SOLAR PHOTOVOLTAIC WATER PUMPING SYSTEM FOR IRRIGATION.

Cloud train	*Total number*	*Monthly average*	*Percent (%)*
1	*1703*	*142*	*62%*
2	*663*	*55*	*24%*
3	*212*	*18*	*8%*
4	*99*	*8*	*4%*
5	*39*	*3*	*1%*
>	*33*	*3*	*1%*

TABLE II. ANNUAL STATISTICAL STUDY ASSOCIATED WITH COMPACT CLOUDS IN A DIRECT SOLAR PHOTOVOLTAIC WATER PUMPING SYSTEM FOR IRRIGATION.

Compact Cloud	*Total number per*	*Monthly average*	*Percent (%)*
1 min.	*756*	*63*	*83%*
2 min.	*126*	*11*	*14%*
3 min.	*22*	*2*	*2%*
4 min.	*7*	*1*	*1%*
5 min.	*0*	*0*	*0%*
> 5min.	*1*	*0*	*0%*

Table I shows the annual statistics for cloud trains. It is evident that a significant number of these events have a duration of 1-2 minutes, representing 86% of all recorded cases.

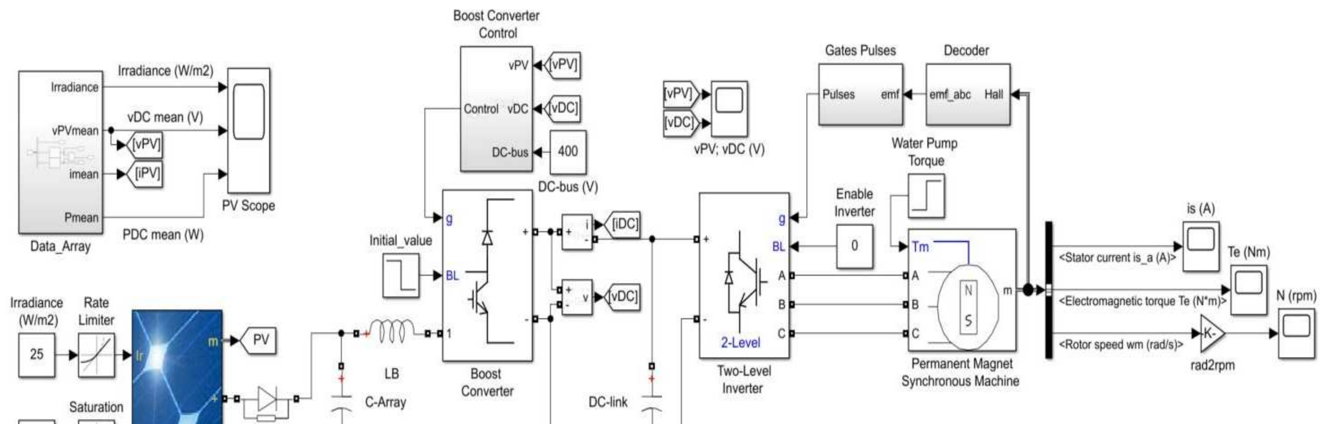

Fig. 9. Stand-alone photovoltaic water pumping system model. The model has been developed in *Matlab/Simulink* software. Temperature (ºC) and irradiance (W/m2) have been considered as input parameters to the system [7].

These events induce frequent stops and starts in the water pumping operation, leading to efficiency losses and mechanical stress on the system components. Table II, on the other hand, presents the frequency of compact clouds. Although less frequent, compact clouds can still cause substantial power drops in the PV-system. Most events last only 1 minute (83%), which suggests brief but sharp irradiance interruptions. These are typically associated with localized meteorological phenomena but can coincide with broader cloud trains under certain conditions.

Meteorological factors such as temperature gradients, wind patterns, and terrain topography play a crucial role in the generation and movement of cloud structures. Low-pressure systems or storms can give rise to both cloud trains and compact clouds at different moments within the same weather event.

TABLE III. ANNUAL STATISTICAL STUDY ASSOCIATED WITH CLOUDY WEATHER (DETECTED EVENTS).

Event time	*Total per year*	*Monthly average*	*Percent (%)*	*Cumulative Percent(%)*
1 min.	*652*	*54*	*32%*	*32%*
2 min.	*325*	*27*	*16%*	*48%*
3 min.	*229*	*19*	*11%*	*59%*
4 min.	*176*	*15*	*9%*	*68%*
5 min.	*119*	*10*	*6%*	*74%*
6min.	*94*	*8*	*5%*	*78%*
7min.	*75*	*6*	*4%*	*82%*

The implementation of an energy storage system (ESS), particularly one capable of supporting the DC-bus for short durations (2-3 minutes), is identified as a key strategy to buffer these transient losses. Statistical data support the conclusion that an appropriately dimensioned ESS -using ultra-capacitors or LiFePO□ batteries- could compensate for the vast majority of cloud-induced interruptions. Ultra-capacitors, in particular, offer high power density and fast charge/discharge cycles, although their cost remains a limiting factor.

Furthermore, Table III introduces a complementary analysis of the temporal spacing between cloudy events, which is crucial when evaluating the recharge capability of the ESS. If two successive cloud passages are separated by only a short time interval, the energy storage device may not have sufficient time to fully recover its charge, compromising its ability to provide continuous support.

These detailed statistical insights help inform the design of robust hybrid PV pumping systems, where data-driven strategies can be applied to determine the required storage size, enhance operational resilience, and reduce mechanical wear caused by frequent power fluctuations.

5. Modeling of proposed system.

A detailed model of a stand-alone photovoltaic water pumping system has been developed using *Matlab/ Simulink*, as depicted in Figure 9. The system comprises a photovoltaic (PV) array, a boost (step-up) converter, a DC-link capacitor, a three-phase voltage source inverter (VSI), a permanent-magnet synchronous motor (PMSM), and a centrifugal water pump. A blocking diode is included to prevent reverse current flow into the PV-array.

The PMSM is responsible for converting the electrical energy supplied by the PV system into mechanical energy to drive the water pump. No energy storage system (ESS) is incorporated in this configuration to reduce cost; however, an ESS could be seamlessly integrated if required for specific operational scenarios. Generally, the PV array is slightly oversized relative to the pump motor power to ensure consistent operation under variable solar irradiance.

A. Modeling of Water Pump

A centrifugal water pump is used in this system. Its torque-speed characteristic is given by:

$$T_P = k_P \cdot \omega_r^2 \tag{6}$$

$$\omega_r = \frac{2\pi}{60}\, n_r \tag{7}$$

where T_P is the pump torque (which is the motor load torque), k_P is the proportionality constant depend on the pump and fluid characteristics, ω_r denotes the rotor mechanical speed (rad/s), and n_r is the rated motor speed (rpm).

B. Modeling of PMSM

The dynamic behaviour of the PMSM is described by the following set of equations:

$$v_d = L_d \frac{di_d}{dt} + R_s i_d - \omega_e L_d i_q \tag{8}$$

$$v_q = L_q \frac{di_q}{dt} + R_s i_q + \omega_e (\lambda_{PM} + L_d i_d) \tag{9}$$

$$T_e = \frac{3}{2} p \left[\lambda_{PM} i_d + \left(L_d - L_q\right) i_d i_q\right] \tag{10}$$

$$J \frac{d\omega}{dt} = T_e - T_L - B\omega \tag{11}$$

where v_d and v_q are the stator voltages in the *d-q* axis. The current and inductance components are denoted by (i_d, i_q), and (L_d, L_q), respectively. λ_{PM} is the magnet flux linkage. The mechanical and electrical angular speeds are depicted by ω and ω_e, respectively. R_s is the stator resistance, T_e is electromagnetic torque, T_L is the load torque, p is the pole pair, J is inertia moment, and B is the friction coefficient.

C. DC-link

The DC-link voltage required by the two-level VSI can be determined by:

$$v_{DC} = \frac{2\sqrt{2}}{\sqrt{3M_i}}\, v_L \tag{12}$$

where, v_L is the line-to-line output voltage (typically 230V), and M_i represents the inverter modulation index (usually taken as 1 in ideal conditions).

D. Boost Converter Modeling

Boost converter is widely used in renewable energy systems to supply power to the DC-bus. The boost converter serves to raise the PV array voltage to the required DC-link voltage level, and also allows for Maximum Power Point Tracking (MPPT) implementation. The voltage gain of the boost converter is given by:

$$v_{DC} = \frac{1}{1-D} v_{PV} \tag{13}$$

$$D = \frac{v_{DC} - v_{PV}}{v_{DC}} \tag{14}$$

where D is the duty cycle, while v_{PV} and v_{DC} are the PV-array voltage and the required DC-link voltage, respectively.

The inductance L_{PV} of the boost converter is calculated based on the maximum current ripple allowed, using the following equation:

$$L_{PV} \geq \frac{v_{PV} \cdot D}{\Delta i_{MPP} \cdot f_{SW}} \tag{15}$$

$$\Delta i_{MPP} = k_{RC} \times N_P \times i_{MPP} \tag{16}$$

where, Δi_{MPP} is the peak-to-peak inductor current ripple at the Maximum Power Point, f_{SW} is the switching frequency of the boost converter, k_{RC} is the ripple current factor (typically 5%), and i_{MPP} is the maximum power current.

6. Conclusion

This paper has presented a comprehensive modeling and simulation of a stand-alone direct photovoltaic water pumping system specifically designed for irrigation purposes. The proposed system, implemented and tested using *Matlab/Simulink*, has been experimentally validated through a real-world setup. One of the key contributions of this work lies in the detailed analysis of cloud transit phenomena and their impact on the performance of the photovoltaic system. The behaviour of the system has been thoroughly evaluated under different operating conditions, including start-up, steady-state, and dynamic transients, both on clear and cloudy days. These simulations confirm the model's robustness and suitability for real-life deployment in agricultural environments with intermittent solar availability.

A significant finding of the study is the limitation of using ultra-capacitor modules as the sole energy buffer. In scenarios of prolonged cloud cover, these components are unable to maintain system operation independently. Therefore, the integration of $LiFePO_4$ batteries is proposed as a reliable solution to ensure continuous operation and system stability under fluctuating irradiance. Furthermore, the study introduces and defines key parameters associated with cloud transit events -such as compact cloud trains and isolated shading intervals- and evaluates their direct influence on the energy yield of the system. These insights provide a valuable foundation for optimizing photovoltaic water pumping systems in environments with variable solar conditions.

Acknowledgement

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