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Effect of cloud transits in a stand-alone solar photovoltaic water pumping system.

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Abstract. This paper discusses the effects of cloud transit on a stand-alone direct solar photovoltaic water pumping system for irrigation and farms. In this way, its impact is studied, applying a possible classification based on its incidence and effects on the system. For this, the information provided by the data loggers of different photovoltaic installations has been analyzed and in turn compared with the data obtained in the reference installation. In addition, the Matlab-Simulink simulation model used is described. Different simulations have been developed to verify the basic characteristics of the proposed system. In this way, it is possible to check the advantages and drawbacks of the direct water pumping in irrigation applications. At the same time, the system parameters can be easily modified to meet the requirements of different water flow capacities. Also, the water hammer effect and the cavitation phenomenon in the water pump are described. Finally, the simulation results obtained as well as their conclusions are presented.

Keywords. Stand-alone solar photovoltaic system, Cloud transit, water pumping system, MPPT Control Algorithm, Efficiency, Energy harvesting, Irrigation, Performance and feasibility analysis, Direct water pumping.

1. Introduction

Some studies have indicated that stand-alone photovoltaic water pumping systems without battery energy storage, are economically viable compared to diesel or gas power generation systems [1] [2], in water supply and irrigation applications in rural, urban, and remote regions. The use of photovoltaic pumping systems is a viable solution to pumping systems based on fossil fuels since they do not require expensive fuels nor do they cause increased air pollution and noise. In addition, they do not contribute to greenhouse gases emission. In this way, solar photovoltaic water pumping systems are more ecological and require little maintenance.

Stand-alone photovoltaic water pumping systems have shown great acceptance and reliability in the water supply for domestic, livestock, and irrigation use in remote areas. In addition, recent studies [3] indicate that the operation and maintenance cost, as well as the replacement cost of a diesel pumping system, is in the order of 2 to 4 times higher than a photovoltaic pumping system [4]. Thus, depending on the application and its characteristics, a hybrid solution may be a better option and more economically viable than a connection to the utility-grid [5]. Figure 1 shows a stand-alone photovoltaic water pumping system for irrigation vineyards. On this occasion, the photovoltaic tracker on the North-South axis allows us to follow the daily East-West path of the sun.

In [1], [2] an exhaustive review of the recent technology applied to solar photovoltaic water pumping is presented, evaluating its economic feasibility, advantages and drawbacks, as well as some restrictions and research gaps in direct water pumping systems. In turn, different pumping systems are presented (surface and submersible pump, direct water pumping, pumping with irrigation tank or support pond, etc.). Some MPPT algorithms are also briefly described to optimize the energy harvested by the photovoltaic array.

Fig. 1. Stand-alone solar photovoltaic water pumping installation for irrigation. Photovoltaic tracker on North-South axis. It allows us to follow the daily East-West path of the sun.

Today, direct photovoltaic water pumping systems have gone from being a promising solution to a reality in many developing countries [6] [7]. Typically, at these facilities, the water is pumped during the day and stored in tanks, for use during the day, at night, or in cloudy conditions.

Several examples of direct photovoltaic water pumping systems can be found in the academic literature [8] [9]. It must also be taken into account that in photovoltaic water pumping installations without batteries, intermittencies or power supply cuts may occur as a result of cloudy days and at night.

In [10] a battery-based solution to improve the efficiency of photovoltaic power supply is described. The sensitivity of some parameters of the models is analyzed in detail [11]. The results presented demonstrate the benefits of including a battery in the supply system. The authors have focused on the performance analysis, optimum sizing, degradation of photovoltaic panels, as well as economic and environmental aspects of these water pumping facilities. Meanwhile, in [12] the impact of horizontal cloud transits on the performance of string-based solar PV power plants is presented. The efficiency study is developed in Matlab. In this way, the effects of power losses, efficiency, and performance ratio are observed.

Fig. 2. Irrigation pond associated with a stand-alone photovoltaic solar water pumping installation.

Similarly, in [13] some simulation models of photovoltaic water pumping systems are described. These models allow us to estimate the efficiency of the water pumping system for different operating points. Thus, the sensitivity of some parameters such as irradiance, temperature, water flow, power supply, minimum energy storage time, etc. can be observed [14]. At the same time, water pump speed control models are introduced.

Another important factor in these water pumping systems is the optimization of renewable resources. Therefore, [15] describes the comparison of single-target and multi-target optimization for photovoltaic water pumping systems. This optimization was carried out using the PSO algorithm. The technical-economic performance indicators such as unused energy, deficit or excess of water, shortage day, etc., vary widely in the case of single-objective optimization.

In the paper presented here, the effect of cloud transit on a stand-alone solar photovoltaic pumping water system for irrigation is analyzed. The document is organized as follows. Section 1 shows a brief introduction to the problem presented and the state-of-the-art. Section 2 describes the impact of the water hammer and the cavitation phenomenon in the water pump. Section 3 provides details on the design of a stand-alone photovoltaic solar water pumping system for irrigation. Thus, the model developed in Matlab-Simulink is presented. Cloud transit analysis is discussed in Section 4. Finally, Section 5 summarizes the conclusions obtained.

2. Water Hammer Effects

In many cases, it is advisable to incorporate a d-HESS (decentralized-Hybrid Energy Storage System) in solar photovoltaic water pumping installations for irrigation, with a dual purpose. On the one hand, it allows us to accumulate in its batteries or ultracapacitors (integrated with the d-HESS) the excess photovoltaic energy harvested for use on cloudy days. While on the other hand, it allows us to guarantee the power supply to the water pump during continuous cloud transits. In this way, it is possible to avoid the successive start-up and stop processes that degrade the hydraulic machine (cavitation phenomenon and water hammer effects). Figure 3 shows typical solar photovoltaic water pumping installations for irrigation and farms. In this way, you can see the different components that make up these irrigation systems.

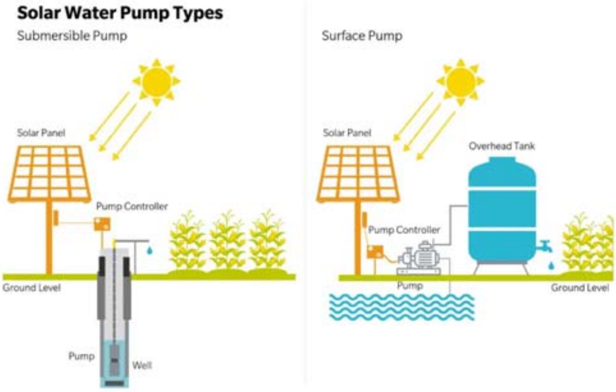

Fig. 3. Typical solar photovoltaic water pumping installations for irrigation and farms.

A. Water Hammer Effects

A water hammer is a physical phenomenon that occurs in any piping system where valves are used to control the water flow. It is the result of the increase in pressure when a moving fluid is forced to change direction or stop abruptly. Thus, the continuous cloud transits cause a decrease in photovoltaic power harvested and therefore, if there is no energy storage, it causes sudden stops in the hydraulic system. Being the main cause of degradation and breakage of the water pump in these facilities.

In these irrigation installations, the analysis of the hydraulic transients is more critical than the analysis of the steady-state system. The pressures during the transient will be higher when the speed changes are more abrupt or sudden, such as during the sudden closing of a valve or the shutdown of the water pump. Thus, this disturbance can be a consequence of the system operation, for example, the stoppage of the water pump due to lack of power supply, generating a pressure increase that can easily overcome the resistance of the irrigation pipe. The water hammer problem is one of the most complex problems in hydraulics, and it is generally solved by means of mathematical models that allow us to simulate the behavior of the system. A rough estimate of the pressure increase ΔH is given by,

$$\Delta H = a \frac{v_W}{g} \tag{1}$$

where, ΔH is the pressure rise (mca), v_W is the average velocity of the fluid (water) at steady-state, g is gravity constant (9.81m/s^2), while a is the relative speed of the wave with respect to the fluid (overpressure or depression effect). In turn, the relative speed of the wave can be obtained as:

$$a = \frac{\sqrt{\frac{K}{\rho}}}{\sqrt{1 + K\frac{D}{E \cdot e}}} \tag{2}$$

where these new parameters are: K is the water elasticity modulus ($2.074 \cdot 10^9$ N/m^2), E is Young's modulus of the pipe which depends on the material, D and e are the diameter and thickness of the pipe respectively, and ρ is the water density (1000kg/m^3).

Thus, the maximum and minimum pressure, at the initial reference point, at the sudden stop it will be given as (Allievi's expression),

$$H_{max} = H_G + \Delta H \quad (mca) \tag{3}$$

$$H_{min} = H_G - \Delta H \quad (mca) \tag{4}$$

where, H_{max} and H_{min} are the maximum and minimum pressures respectively, while H_G is the geometric height (mca). 1atm = 1.01bar = 10.33mca.

This phenomenon is dangerous since the overpressure generated can be higher than 50/75 times the steady-state pressure in the pipeline, causing damage and breaks in the different joints and irrigation pipelines.

B. Cavitation Phenomenon

Cavitation is a phenomenon by which bubbles are produced in a fluid as a consequence of changes in pressure or temperature. When the internal pressure of a water pipe drops below atmospheric pressure, a vacuum is produced. Thus, pumping becomes inefficient. Cavitation in a water pump for irrigation is one of the most frequent problems.

This phenomenon is often accompanied by vibrations and noise. A possible cause may be an incorrect design in the pumping system. To solve this problem, fluid mechanics (Bernoulli's equation) is applied.

3. System Description

The proposed photovoltaic water pumping system consists of photovoltaic panels, a submersible or surface centrifugal pump, a three-phase induction motor, a battery pack, and an interconnected irrigation pipes network. The schematic diagram of a stand-alone photovoltaic water pumping system for irrigation with battery energy storage is shown in Figure 4.

If a brief comparative analysis is carried out between a direct solar photovoltaic water pumping installation without storage and its equivalent solution with battery-based storage, it is possible to draw some conclusions. In photovoltaic pumping systems with energy storage, it is possible to ensure a continuous and sustainable water supply based on the harvesting of photovoltaic energy. An irrigation application of the stand-alone photovoltaic water pumping system is shown in Figure 5. Its main advantage is to continue pumping water regardless of weather conditions such as cloud transits or adverse irradiance conditions (cloudy). In this way, the current supply necessary to start the water pump and its operation in adverse weather conditions is continuously guaranteed. The system avoids the stop/start cycles of the pump caused by cloud trains and the reduction in energy harvested by the photovoltaic panels. On the other hand, by having a battery pack, the pump could work for a longer time, so a less powerful water-pumping system would be needed for the same design conditions.

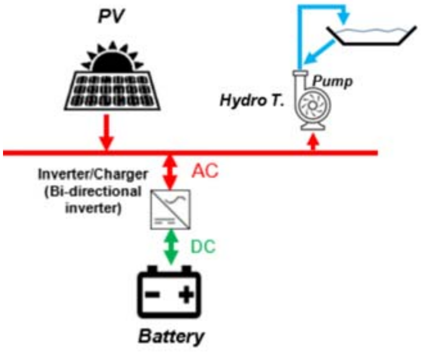

Fig. 4. Stand-alone solar photovoltaic water pumping system supported by battery energy storage system. The battery pack can be replaced by an ultracapacitor pack, as long as the design of the energy storage system allows it.

The main disadvantage of the photovoltaic water pumping system with a battery energy storage system is that the system is more expensive and less reliable. Since the number of components of the installation is greater (charge regulator, boost converter, MPPT control, inverter, batteries, etc.) and therefore the maintenance required by the installation will also be greater. Then the complexity of the system increases. Finally, the overall efficiency of the system decreases. In this way, the global efficiency of the system "η_G" can be represented as:

- solar photovoltaic array efficiency "η_{PH}",

$$\eta_{PH} = \frac{i_O \cdot v_O}{G \cdot A \cdot n_S \cdot n_p} \tag{5}$$

- electric drive efficiency "η_{ED}",

$$\eta_{ED} = \frac{P_M}{P_{PH}} \tag{6}$$

- water pump efficiency "η_H",

$$\eta_H = \frac{\rho \cdot g \cdot h \cdot Q}{P_M} \tag{7}$$

where, v_O and i_O are the output voltage and output current in the solar photovoltaic module, n_S is the number of cells connected in series while n_P is the number of cells connected in parallel, G is the solar irradiance (W/m^2) and A is the surface of the solar photovoltaic array (m^2), P_M is the motor shaft power (W) and P_{PH} is the power supplied by the photovoltaic array (W). Finally, g is gravity constant (9.81m/s^2), h is the pump's total head (m), Q is required water flow (m^3/h), and ρ is the water density (1000kg/m^3). Thus, the overall efficiency is obtained as,

$$\eta_G = \eta_{PH} \times \eta_{ED} \times \eta_H \tag{8}$$

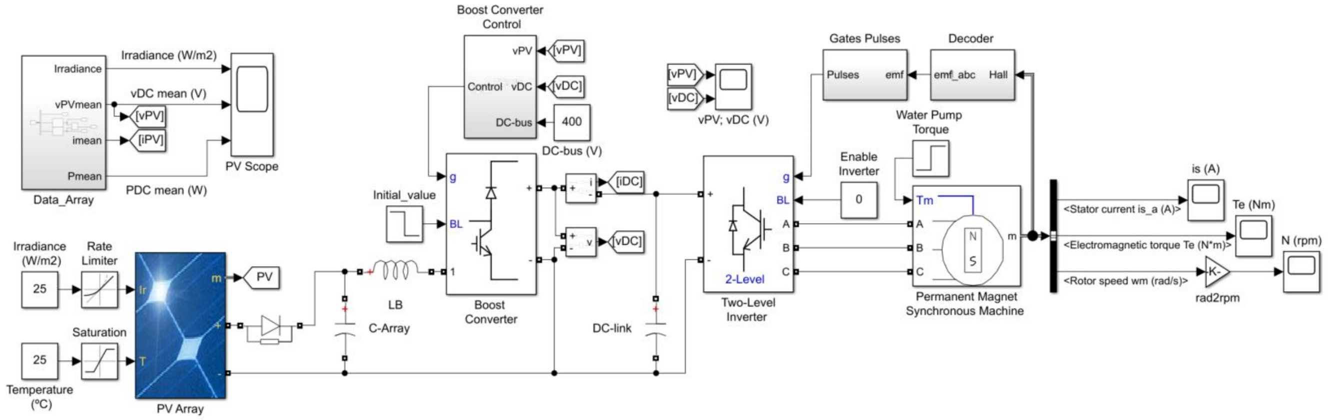

Fig. 5. Stand-alone photovoltaic water pumping system model. The model has been developed in Matlab/Simulink software. Temperature (ºC) and irradiance (W/m^2) have been considered as input parameters to the system.

Fig. 6. Water pumping application for irrigation.

Different electric motors can be used to drive the water pump. Among the most popular are asynchronous induction motors, brushless motors, as well as permanent magnet synchronous motors. For small powers (up to several kilowatts), the most used motors are those that are maintenance-free. A model of a stand-alone photovoltaic water pumping system developed in Matlab/Simulink is shown in Figure 5. In this case, the electrical machine used to drive the water pump has been a permanent magnet synchronous motor (PMSM). To simulate the operation of the water pump, a resistant torque "T_M" has been requested in the motor (9).

$$T_M = \frac{60}{2\pi}\,\frac{P_M}{n_M} \tag{9}$$

where n_M is the speed of the permanent magnet synchronous motor (rpm). Generally, the efficiency of the water pump (η_H) is usually considered around 65-70%. In this way, if the height of the irrigation well is $h = 25$m, a water pump efficiency of $\eta_H = 0.65$, and a motor speed of $n_M = 1500$rpm approx. are considered, then it is possible to obtain the motor power P_M and motor torque T_M depending on the required water flow rate Q. The different operating points of the irrigation system are shown in table I.

Usually, the power rating of the solar PV array is selected to be slightly higher than the power required by the pump motor. Thus, the number of photovoltaic panels connected in series n_S or parallel n_P depends on the parameters of the selected photovoltaic module. Some parameters of SW250 photovoltaic module, manufactured by Sunmodule, under standard test conditions (1000W/m^2 STC insulation and 25°C ambient temperature) are shown in Table II.

TABLE I. POWER AND TORQUE VERSUS THE WATER FLOW REQUIRED FOR IRRIGATION.

Water Flow Q(m^3/h)	*Power P_M(kW)*	*Torque T_M(Nm)*
12,5	*1,31*	*10*
10	*1.05*	*6.67*
7.5	*0.786*	*5*
5	*0.524*	*3.34*
2.5	*0.26*	*1.66*

TABLE II. SW250 SOLAR PV MODULE SPECIFICATIONS

Parameter	*1000W/m^2*	*800W/m^2*
Maximum Power P_{MPP}	*250Wp*	*184.9Wp*
Open Circuit voltage v_{OC}	*37.6V*	*34.4V*
Maximum power voltage v_{MPP}	*30.5V*	*27.9V*
Short Circuit current i_{SC}	*8.81A*	*7.12A*
Maximum power current i_{MPP}	*8.27A*	*6.62A*

4. Cloud Transit

In general, solar photovoltaic systems are subject to power losses due to the passage of clouds. Cloud trains are short clouds that follow each other quickly for a few seconds or a few minutes. Clouds can reduce the irradiance level of photovoltaic modules from 800W/m^2 to 400W/m^2 and even 200W/m^2 depending on their intensity. During this period, sunny and cloudy alternate successively. The power loss (%) of the solar photovoltaic system during cloud shading can be determined as,

$$P_{Loss} = \frac{P_N - P_{MPPT}}{P_{MPPT}} \times 100\ (\%) \tag{10}$$

where P_N and P_{MPPT} represent the power generated with partial shading and the output power under optimal conditions (without shade), respectively.

When a cloud passes, the irradiance can drop to approximately 75% in a few seconds (see Figure 7), which means a decrease in power in the photovoltaic system. A control technique used in direct pumping systems, in order to avoid cloud passage and power loss, is to decrease the frequency of the water pump. In this way, the water flow supplied to irrigation is reduced as also its consumption.

Thus, the shutdown of the system is avoided and the cloud pass is overcome.

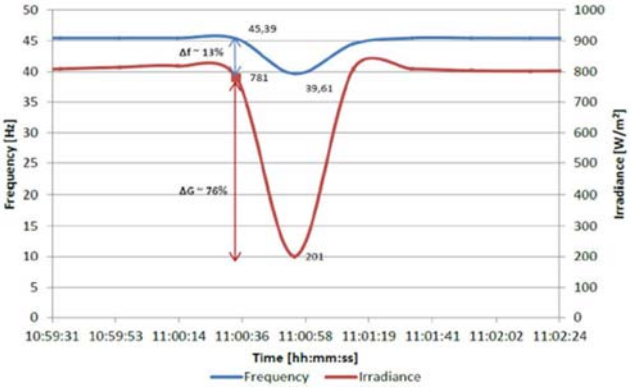

Fig. 7. Irradiance and frequency of the water pump during a cloud passage.

Thus, the irradiance and its oscillations on cloudy days cause sudden variations in the power supply in the water pumping and in turn, are transmitted almost instantaneously to the pressure system (direct pumping systems). These sudden fluctuations can cause pressure waves that are transmitted from the water pump to the hydraulic system. Increased pressure in the hydraulic system can cause water hammer and decreased pressure can cause cavitation in the water pump. Both phenomena degrade the water pump and cause fatigue in the hydraulic system valves, causing irreversible damage over time.

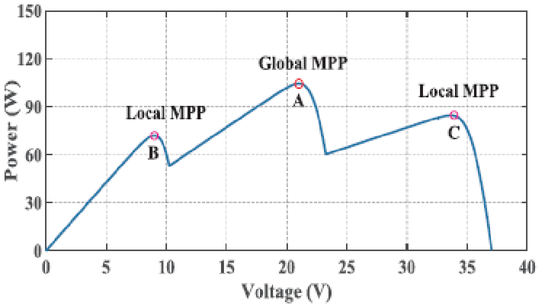

Fig. 8. Power vs. voltage (*P*-*v*) characteristics curve in the photovoltaic array during cloud passage, and several local maximum power points appear on the curve.

The incorporation of energy storage systems in the DC-bus (based on batteries or ultracapacitors) allows us to solve the cloud transit problem. Figure 8 shows the decrease in energy harvested in the photovoltaic system. In addition, this partial shading gives rise to some local maximum power points and therefore to a decrease in the efficiency of the control system (maximum power point tracking).

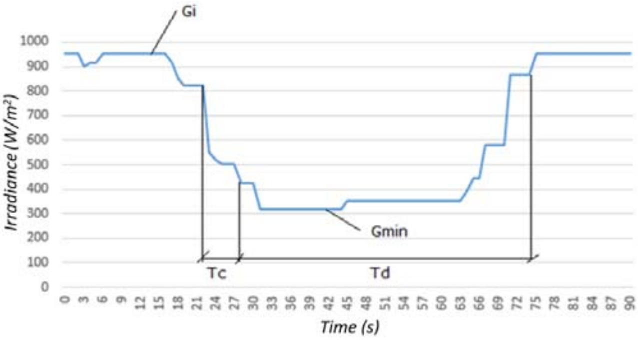

Fig. 9. Modeling and definition of cloud transit parameters.

The parameters and modeling of the cloud transit can be seen in Figure 9. Thus, the different stages of cloud transit and its disturbance on the photovoltaic system are:

- Initially, there is a high irradiance "G_i" (around $G_i \geq 900\text{W/m}^2$) which corresponds to a clear sky (no clouds).
- During time "T_c" the cloud begins to partially cover the photovoltaic array, so the irradiance drops quickly.
- The photovoltaic array is already completely covered and its "G_{min}" irradiation is minimal (around $G_{min} \leq 300\text{W/m}^2$).
- The duration "T_d" of the cloud transit corresponds to the time that the photovoltaic array recovers the initial irradiance "G_i".

The parameters T_c and T_d have an influence on the design of the hybrid energy storage system (hESS) since they determine the minimum energy that the ultracapacitor pack must store so that the sudden stop of the water pump does not occur. Figure 10 shows a direct photovoltaic water pumping system for irrigation. You can see the different elements and pipes of the pumping system.

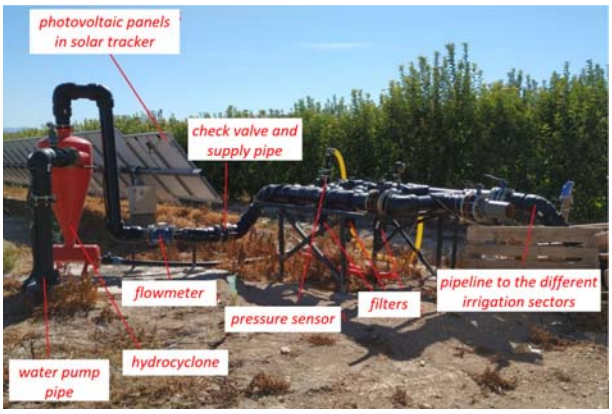

Fig. 10. Example of hydraulic installation of direct photovoltaic irrigation. Different elements make up the photovoltaic water pumping system.

Ultracapacitor packs offer higher power density and cycling capacity than battery packs (although their cost is higher), so they are a good choice in industrial applications that require fast charge/discharge processes. Thus, the energy stored in the ultracapacitor package E_{UC} will be given by,

$$E_{UC} = \frac{1}{2} C_{UC}(v_{max}^2 - v_{min}^2) \tag{11}$$

where, C_{UC} is the ultracapacitor pack capacity, while v_{max} and v_{min} are the maximum and minimum voltage of the DC-link (ultracapacitor voltage variation range Δv), respectively. In this case, the maximum voltage coincides with the DC-bus voltage ($v_{max} = +v_{DC}$), while the discharge time will be equivalent to T_d (time estimated in the cloud transit model). Thus, the capacity of the ultracapacitor pack required will be given by,

$$C_{UC} = \frac{2 \cdot P_{PH} \eta_{ED} \cdot T_d}{v_{DC}^2 - v_{min}^2} \tag{12}$$

In the case of a cloud train (several continuous cloud transits) or a compact cloud, the energy stored in the ultracapacitor pack would be insufficient to keep the water pump running during the time interval. However, there is enough time to turn off the water pumping system in a controlled manner. The use of a battery-based energy storage system allows us to solve this situation, although the costs of the water pumping system have increased. To ensure irrigation, on those cloudy days, many facilities have fossil fuel generators since their cost is lower than the battery pack.

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

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

As a summary, Table III shows an annual statistical study of cloud trains, according to their temporal duration in a vineyard irrigation facility. This direct photovoltaic water pumping system is located in Cariñena (Spain). As can be seen, the number of cloud trains is very high, which means continuous stops and starts of these irrigation systems.

The design of the energy storage system (hESS) depends on the type of irrigation installation and water pumping power, although it is possible to connect storage devices in parallel. In general, the minimum irradiance reached during cloud transit has a value similar to 250-300W/m^2 (STC standard irradiance is 1000W/m^2). Therefore, in most cases, the energy storage system must supply the power to soft stop the water pump according to the implemented control algorithm.

5. Conclusion

In this paper, the model of a stand-alone direct photovoltaic water pumping system for irrigation is presented. The model has been simulated in Matlab-Simulink and checked with the experimental setup. At the same time, the effects of cloud transit on the photovoltaic system have been analyzed. Its performance has been checked under starting, stationary and dynamic conditions (sunny and cloudy days). Finally, the cloud transit parameters have been defined and their effects on the harvested energy have been studied.

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