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Modeling of a stand-alone solar photovoltaic water pumping system for irrigation

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Abstract.
Solar photovoltaic water pumping systems have been research topics in recent decades. The purpose was to develop much more profitable and efficient systems to meet the needs of pumping water for livestock and irrigation. This paper describes the design of a stand-alone photovoltaic water pumping system. A Boost converter is used to apply the Maximum Power Point Tracking (MPPT) algorithm. Similarly, a three-phase voltage source converter (VSC) is used to supply the asynchronous motor. The installation must provide a continuous water flow during the irrigation interval. It has been verified that in adverse weather conditions (cloud transits or partly cloudy) it is necessary to incorporate a decentralized-hybrid energy storage system (based on batteries or ultracapacitors), or excessively oversize the stand-alone photovoltaic system, to supply the water pump. The model has been simulated in Matlab-Simulink. In this way, different simulations have been developed to verify the basic characteristics of the proposed system. The results of the simulated model and the conclusions obtained are also presented in this paper.

Keywords. Solar photovoltaic, water pumping systems, decentralized Hybrid Energy Storage System (dHESS), Irrigation, MPPT Control Algorithm, Efficiency, Reliable, Partial shading, Energy harvesting, Performance analysis.

1. Introduction

In this decade, solar photovoltaic water pumping systems are being studied as a viable and economical option. Some studies indicate that photovoltaic water pumping is economically feasible compared to electricity or diesel generation systems for irrigation and water supply in rural, urban and remote regions. Photovoltaic water pumping reduces the dependence on diesel or gas-based electricity generation. The use of pumping systems based on fossil fuels not only requires expensive fuels but also produces an increases in air pollution and noise. The electricity deficit and high diesel costs affect pumping requirements in irrigation communities. In these stand-alone water-pumping applications, solar photovoltaic technology can be an alternative to the classic diesel generators that exists on many farms. The purpose is to make these systems more efficient and cost-effective to meet the water pumping needs of people, livestock, and irrigation [1].

Photovoltaic installations applied to water pumping in places where the utility grid is not available have some advantages, such as the abundance of energy and the lower cost of the installation. Furthermore, some studies [2], [3] indicate that the cost of maintenance and operation as well as the replacement of a diesel pumping system is in the order of 2 to 4 times higher than a photovoltaic pumping system. On the other hand, solar pumping systems are environmentally friendly and require little maintenance. Figure 1 shows a photovoltaic water pumping system for irrigation vineyards.

Fig. 1. Installation of solar photovoltaic water pumping for irrigation of a vineyard in Cariñena (Spain).

At present, different installations and even techniques can be used to convert solar photovoltaic energy into mechanical or electrical energy to drive water pumps. In [1], the authors present a review of the technology associated with photovoltaic water pumping systems. Thus, the maximum power point tracking (MPPT) algorithm, the different pumps and motors used, and a brief classification of photovoltaic (PV) panels are described in detail. All these parameters affect the performance, efficiency, and ultimately, the profitability of the photovoltaic water pumping system. Likewise, in [2] an exhaustive review of solar pumping technology is presented, evaluating its applicability and economic viability, and identifying some restrictions and research gaps in these water-pumping systems. Unlike the previous case, this study has focused on the performance analysis, optimal sizing, degradation of photovoltaic panels, as well as economic and environmental aspects of these pumping installations [3]. In this way, the research work developed by some researchers related to the use of photovoltaic solar energy in this context is analyzed.

Usually in these facilities the water is pumped during the day and stored in tanks, for use during the day, at night, or in cloudy conditions [4], [5]. In this way, the water tank acts as storage and, in general, the battery is not used for the storage of photovoltaic energy. Centrifugal submersible pumps or helical motor pumps are often used in these applications, due to their reliability and low maintenance. Furthermore, it should be noted that the capacity of a photovoltaic pumping system is a function of three main variables: pressure, water flow, and pump power. Therefore, the pump only needs a certain power to produce a certain amount of pressure and water flow, that is, the dimensions of the photovoltaic field must be optimized to generate the amount of energy required.

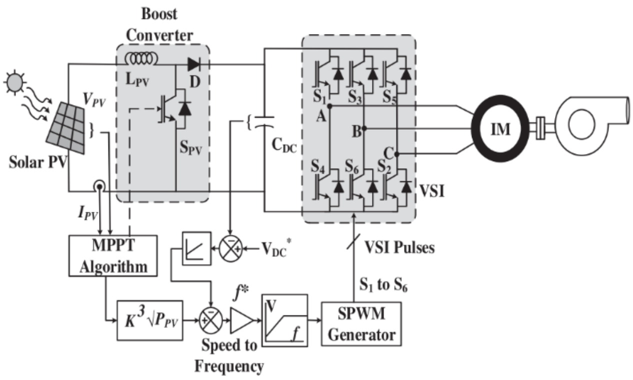

Fig. 2. Typical architecture of a stand-alone solar water pumping system [3].

In recent years, many attempts have been made to design stand-alone photovoltaic powered water pumping systems applying different control techniques and motor drives in various power electronics architectures, with and without battery energy storage [6], or with reconfiguration loops in the photovoltaic modules [7]. A typical architecture of a stand-alone solar water pumping system is shown in Fig. 2. It should also be noted that in photovoltaic water pumping installations without batteries, intermittences or supply cuts may occur as a result of cloudy and night conditions. In this scenario, the amount of water accumulated in the irrigation tank or in the drinking water distribution reservoir may be insufficient. However, the use of energy storage modules makes the system more expensive and requires regular maintenance. Figure 3 shows some lead-acid batteries and inverters associated with a stand-alone photovoltaic solar water pumping system for irrigation.

In direct-drive photovoltaic water pumping installations, all the electricity obtained from the photovoltaic modules is supplied directly to the pump. Since there is no energy storage system, the system pumps water during the day when solar energy is available. The intensity of the solar radiation that falls on the photovoltaic panel provides the amount of water pumped during this period of time. The main advantage of this system is that it does not require batteries, therefore it is simple and low cost. On the other hand, the use of battery energy storage systems ensures the possible pumping of water even in periods of low light, cloudy days, and also at night.

As a novelty, at present, the differential power processing architecture based on DC converters has been analyzed to optimize the power capture of photovoltaic modules [8]. Now, the control algorithm is oriented to achieve that each PV module/array reaches its optimal operating point, under non-uniform irradiance conditions [9], [10]. With inhomogeneous irradiation, the efficiency of PV modules decreases significantly. Thus, the concept of distributed-Maximum Power Point Tracking (dMPPT) is considered an effective solution against this mismatch. Meanwhile, in [11] a MISO architecture, based on SEPIC converters, is proposed to maximize the extraction of available PV power even under mismatch conditions, i.e. partial shading, cloudiness, dust, aging, or enveloping shading (SSE). Similarly, in [12] is presented an improved control technique applied to a switched reluctance motor (SRM) within a single-phase water-pumping photovoltaic system. The system's PV power supply is supported by the grid. Its novelty is the implemented control method that makes the water-pumping system more efficient and reliable.

Fig. 3. Batteries and inverters associated with a stand-alone solar photovoltaic water pumping system for irrigation, [13]. Viñas del Vero facility located in Barbastro (Zaragoza); LIFE+REWIND Project.

In the paper presented here, the modeling and design of a photovoltaic water pumping system for irrigation is analyzed. The document is organized as follows. Section I shows a brief introduction to the presented problem and the state-of-the-art. Section II gives a description about the system configuration, therefore this section deals with the design of a solar photovoltaic water pumping system for irrigation. The simulation results are shown in Section III. Finally, Section IV summarizes the conclusions obtained.

2. System Design

The schematic diagram of a photovoltaic water pumping system for irrigation is shown in Fig. 2. This system consists of photovoltaic modules, a DC step-up converter (usually a Boost converter), and a VSC inverter that supplies the water pump. The design of the different elements is explained in the following subsections.

A. Selection of Water Pump Rating

The water pump is chosen according to the required water flow and the total dynamic head available. Thus, the required pump power "P_P" is calculated as:

$$P_P = \frac{\rho g h Q}{3,6 \times 10^6} \quad (kW) \tag{1}$$

where g is gravity constant (9.81m/s^2), h is total height (m), Q is required water flow (m^3/h), and ρ is the water density (1000kg/m^3). Generally, the efficiency of the water pump (η_P) is usually considered around 65-70%. Thus, the motor shaft power "P_M" is obtained as:

$$P_M = \frac{P_P}{\eta_P} \quad (kW) \tag{2}$$

In this way, if the necessary water flow and the height of the irrigation well are $Q = 12.5$m^3/h and $h = 25$m respectively, and considering a pump efficiency $\eta_P = 0.65$, then the required motor power will be $P_M = 1.5$kW approx.

B. Selection of Photovoltaic Modules

If the power losses in the machines are neglected, the capacity of the photovoltaic array should be equivalent to the motor power. Thus, the size of the photovoltaic module used for solar water pumping will depend on the size of the load. Usually, the power rating of the solar PV array is selected to be slightly higher than the power required by the pump motor.

In this case, to supply power to the water pump, a 2.5kWp photovoltaic array was selected. A standard SW250 PV module, manufactured by Sunmodule, is chosen for the photovoltaic array design. Some parameters of the SW250 PV module, under standard test conditions (STC insulation 1000W/m^2 and ambient temperature 25°C) are shown in Table I and Table II.

TABLE I. 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*

TABLE II. THERMAL CHARACTERISTICS OF SW250 PV MODULE

Parameter	*Value*
Nominal Operating cell Temp NOCT	*46ºC*
Temp. Coefficient i_{SC}	*0.051%/K*
Temp Coefficient v_{OC}	*-0.31%/K*
Temp. Coefficient P_{MPP}	*-0.41%/K*
Operating Temperature	*-45ºC to 85ºC*

If the selected power of the PV array is $P_{MP} = 2.5$kW, the number of photovoltaic modules required will then be:

$$N = \frac{P_{MP}}{P_{MPP\_SW250}} = 10 \tag{3}$$

If a maximum photovoltaic array voltage of $v_{PV} = 300$V is considered, then the number of PV modules connected in series "N_S" is,

$$N_S = \frac{v_{PV}}{v_{MP\_SW250}} \cong 10 \tag{4}$$

Meanwhile, the number of PV modules connected in parallel "N_P" is,

$$N_P = \frac{P_{MP}}{N_S \times v_{MP\_SW250} \times i_{MP\_SW250}} \cong 1 \tag{5}$$

C. Design of Step-up Converter

Boost converter is widely used in renewable energy systems to supply power to the DC-bus. In this case, the input voltage available at the boost converter is the voltage (v_{PV}) of the PV array. Equation 6 shows the voltage gain of the boost converter. The purpose of this architecture is to apply the MPPT (Maximum Power Point Tracking) algorithm,

$$v_{DC} = \frac{1}{1-D} v_{PV} \tag{6}$$

where D is the duty cycle of the converter, while v_{PV} and v_{DC} are the PV array voltage and the required DC-link voltage, respectively. An asynchronous motor is chosen to drive the water pump. This induction motor has a phase-phase voltage of $v_L = 230\text{V}_{\text{rms}}$. Thus, the necessary DC-bus voltage is obtained as,

$$v_{DC} = \frac{\sqrt{2}}{m} v_L \tag{7}$$

In this case, considering a modulation index $m = 0.85$, a DC-link voltage $v_{DC} = +400$V is adopted. Then, the duty cycle D for the boost converter will be given by (8).

$$D = \frac{v_{DC} - v_{PV}}{v_{DC}} \tag{8}$$

Therefore, according to the initial conditions, the duty ratio (D) of the DC converter will be D > 0.25.

Fig. 4. Photovoltaic panels located on a solar tracker and floating photovoltaic modules. Stand-alone solar photovoltaic water pumping system for vineyard irrigation, [13]. LIFE+REWIND Project.

The boost converter coil "L_{PV}" (see Fig. 2) is estimated as

$$L_{PV} \geq \frac{v_{PV} \times D}{\Delta i_{MPP} \times f_{SW}} \tag{9}$$

$$\Delta i_{MPP} = k_{RC} \times N_P \times i_{MPP} \tag{10}$$

where D is the duty cycle, f_{SW} is the inverter switching frequency ($f_{SW} = 25$kHz), k_{RC} is the current ripple factor in the coil (typical value $k_{RC} = 5\%$), while Δi_{MPP} is the value current ripple estimate (A). Therefore, the standard inductor value is selected as $L_{PV} = 8.2$mH.

Similarly, the DC-link capacitor "C_{DC}" (see Fig. 2) can be estimated as

$$C_{DC} \geq \frac{I_O}{2\omega_e \times \Delta v_{DC}} \quad (11)$$

$$I_O = \frac{P_{MP}}{v_{DC}} \quad (12)$$

$$\Delta v_{DC} = k_{RV} \times v_{DC} \quad (13)$$

where I_O is the DC-bus current, ω_e is the angular frequency ($\omega_e = 2\pi f_G = 314.16$rad/s), k_{RV} is the voltage ripple factor in the capacitor (typical value $k_{RV} = 2.5\%$), while Δv_{DC} is the value voltage ripple estimate (V). Therefore, the standard capacitor value is selected as $C_{DC} = 1200\mu$F.

D. Design of Centrifugal Pump

In the proposed topology, a centrifugal water pump has been used. The water pump is coupled to the asynchronous motor shaft. Some of the design parameters have been summarized in Table III and Table IV. In a centrifugal pump [14], the load torque "T_P" is proportional to the square of the shaft rotation speed (ω_r).

$$T_P = k_P \times \omega_r^2 \quad (14)$$

$$k_P = \frac{T_P}{\omega_r^2} \quad (15)$$

$$\omega_r = \frac{2\pi}{60} n_r \quad (16)$$

where T_P is the load torque on the water pump ($T_P = 10$Nm), k_P is the pump constant, ω_r is the angular frequency, and n_r is the rated motor speed (rpm). Thus, the value of the water pump constant is $k_P = 0.0446\times10^{-3}$Nm/(rad/s)^2.

TABLE III. ASYNCHRONOUS MOTOR SPECIFICATIONS

Parameter	*Value*
Rated Power P_M	*1.5kW*
Rated speed n_M	*1439rpm*
Number of poles	*4 poles*
Frequency f	*50Hz*
Power Factor cosφ	*0.9*
Torque T_M	*9.9Nm*
Nominal Voltage v_L	*230V_{rms}*

TABLE IV. CENTRIFUGAL PUMP SPECIFICATIONS

Parameter	*Value*
Rated Pumping Flow Q	*12.5m^3/h*
Rated Pumping head h	*25m*
Efficiency η_P	*0.65*
Pump constant k_P	*0.044×10^{-3}Nm/(rad/s)^2*

E. Inverter Modulation Strategy

In the inverter, an important factor is the modulation index "*m*", since this parameter is related to the PWM modulation technique. In this case, carrier-based SPWM strategy has been chosen. In this method, the control signals are obtained by comparing the carrier waveform (triangular or sawtooth) and the reference sinusoidal waveform (SPWM technique). In linear mode, this modulation index adopts values between $0 \leq m \leq 1$. Meanwhile, in overshoot mode (non-linear operation), the index *m* is greater than 1. This index m is the ratio between the peak voltages of the reference sine wave "$\widehat{v_{SW}}$" and the triangular carrier wave "$\widehat{v_{TW}}$", respectively, eq. 17. A modulation index $m = 0.85$ has been considered.

$$m = \frac{\widehat{v_{SW}}}{\widehat{v_{TW}}} \quad (17)$$

In general, the selection of the modulation technique allows us to improve the operation of the inverter [15]. Thus it is possible to improve its dynamic response or its harmonic content (THD), reduce its switching losses or increase its efficiency. Some of these techniques are shown in Fig. 5. It should also be noted that although the phase voltages are not sinusoidal, their composition in the motor winding is a sinusoidal waveform.

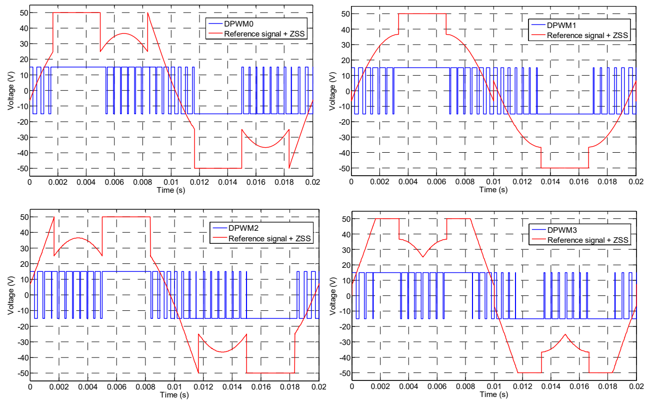

Fig. 5. Discontinuous modulation waveforms (DPWM0, DPWM1, DPWM2 & DPWM3 techniques) vs. reference wave with zero sequence signal injection (ZSS), [15] [16].

The distribution of power losses in the different inverter devices has also been studied. The selected device has been the SK20GD066ET, manufactured by Semikron. This IGBT module is recommended for typical motor applications (<4kW). Some design parameters have been summarized in Table V.

TABLE V. SK20GD066 INVERTER MODULE SPECIFICATIONS

Parameter IGBT	*Value*
Collector-Emitter voltage v_{CE}	*600V*
Collector current i_C (T = 70ºC)	*25A*
Threshold voltage $v_{GE}|_{th}$	*5.8V*
Collector Resistor r_{CE} (v_{GE} = +15V)	*27.5mΩ*
Gate resistor R_G	*15Ω*
Collector-emitter voltage (Saturation) $v_{CE(sat)}$	*1.45V*
Gate capacitor C_{ies}	*1.1nF*

Figure 6 shows the power losses associated with each device under nominal operating conditions (see details in Table III). In this analysis, an overload factor of $k_{OL} = 1.25$ has been considered. The power losses in each IGBT and diode are $P_{IGBT} = 3.52$W and $P_D = 0.59$W, respectively. Thus, the inverter has total power losses of $P_{INV} = 24.67$W and a global efficiency of $\eta_{INV} = 98.38\%$ approx.

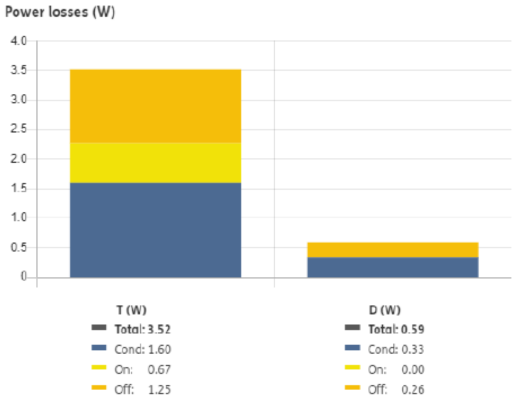

Fig. 6. Distribution of power losses in the devices (IGBT and diode) in the case studied.

3. Simulation Results

A photovoltaic water pumping system has been modelled using Matlab/Simulink. Its performance has been validated during start-up, steady state, and dynamic conditions (sunny and cloudy days). Thus, the results obtained are shown in the following diagrams.

Figure 7 shows the typical energy demand based on the irrigation system's schedule hours. Initially, it has been proposed that the photovoltaic water pumping installation work from 10:00 a.m. to 6:00 p.m. As indicated, battery energy storage has not been considered.

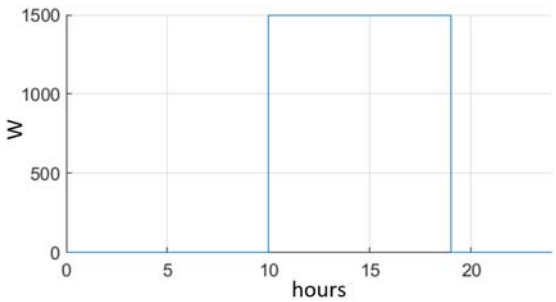

Fig. 7. Typical power demand based on scheduled irrigation hours.

The power harvested by the photovoltaic modules on a standard sunny day is shown in Fig. 8. During the results analysis, in order to reduce the computation time, a discrete photovoltaic function has been considered. While the power balance and power deficit in the photovoltaic water pumping installation are represented in Figs. 9 and 10. As can be seen, during the day there are hourly intervals where the energy harvested is insufficient to supply the water pumping system.

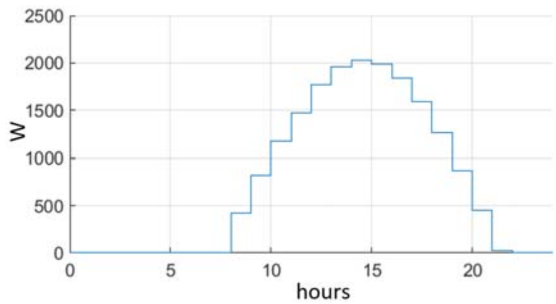

Fig. 8. Power supplied by photovoltaic modules on a sunny day.

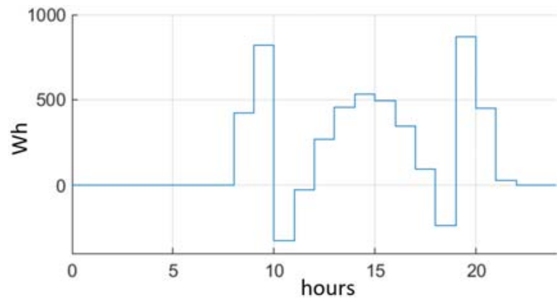

Fig. 9. Power balance in the photovoltaic water pumping system on a sunny day.

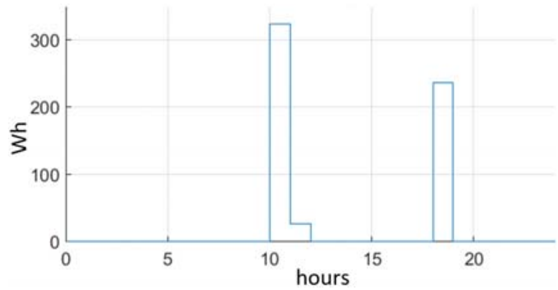

Fig. 10. Power deficit in the photovoltaic water pumping system on a sunny day.

Similarly, the energy harvested by the PV modules on a standard cloudy day is shown in Fig. 11. While, in this case, the power balance and the power deficit in the photovoltaic water pumping installation are represented in Figs. 12 and 13. As can be seen, during a cloudy day the energy harvested is insufficient to supply the water pumping system. An effective solution is to use irrigation rafts or water tanks to guarantee their supply.

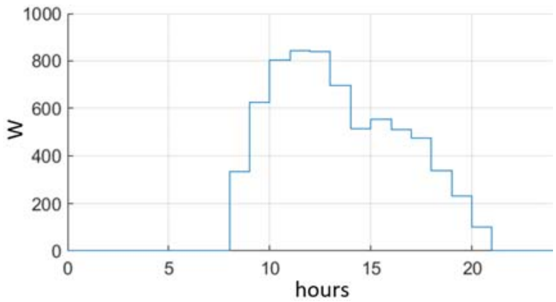

Fig. 11. Power supplied by photovoltaic modules on a cloudy day.

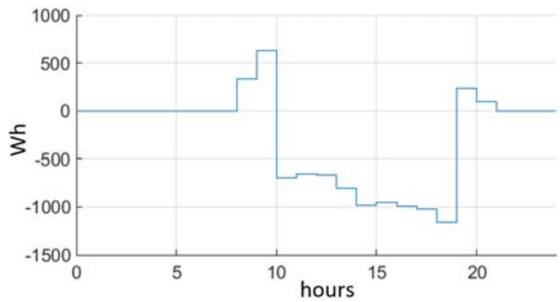

Fig. 12. Power balance in the photovoltaic water pumping system on a cloudy day.

For this reason, in many cases, it is advisable to incorporate a d-HESS (decentralized-hybrid energy storage system), based on batteries or ultracapacitors, which allows us to accumulate excess photovoltaic energy. The purpose is to supply the water pump during cloud transits and avoid successive start-up and stop processes that degrade the machine (cavitation and water hammer effects). A water hammer is a physical phenomenon that occurs in any piping system where valves are used to control the flow of water. It is the result of the increase in pressure when a moving fluid is forced to change direction or stop abruptly. Cloud transits and their sudden stops are the main cause of degradation and breakage of the water pump in these facilities.

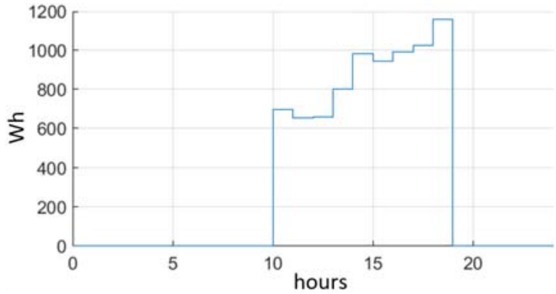

Fig. 13. Power deficit in the photovoltaic water pumping system on a sunny day.

4. Conclusions

In this paper, the design and modeling of a stand-alone solar photovoltaic water pumping system for irrigation have been addressed. The model has been simulated in Matlab-Simulink. Its performance has been validated during start-up, steady-state, and dynamic conditions (sunny and cloudy days).

The decrease in the cost of photovoltaic panels has caused the oversizing of the photovoltaic array and the elimination of the energy storage system (usually based on lead-acid batteries) in many rural installations. Always considering that there are no space problems in the rural environment. As they do not have an energy storage system, these facilities are very sensitive to cloud transits. The successive sudden start and stop processes (caused by cloud trains) are the main cause of degradation and breakage of the water pumps in these rural facilities.

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