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Integration of Supercapacitors in A Solar Photovoltaic Water Pumping System: Case of Koyli Alpha Village, In Ferlo, Senegal

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Abstract: In this article, we had made a study on operation of two solar PV water pumping systems: one without supercapacitors and another with supercapacitors in the storage. This technology, which has been used for years in the transport sector, particularly when starting and braking vehicles, metros and trams, could have applied to an autonomous pumping system installed on the Koyli Alpha site, in the Ferlo area, in Senegal. Photovoltaic solar water pumping systems widely used asynchronous motors. This high current demand when starting the group pump motor caused excessive energy consumption from batteries and leads to a quickly reduction on number of cycles and lifetime of batteries. Thus, for the optimization of this system, we integrate supercapacitors in order to provide an optimal response to boreholes' operation. This study, which uses meteorological hourly data from Koyli Alpha, is carried out on the Simulink / Matlab interface. The simulation results showed a contribution in power from supercapacitors and a decrease in the share of batteries at start-up as well as daily discharge rate. The importance of supercapacitors in this photovoltaic solar water pumping system has allowed an increase of the lifetime of the batteries because it is expected a power gain estimated at 7% on the total capacity of the batteries.

Keywords: Supercapacitors; optimization; Solar Photovoltaic; Water Pumping

1. Introduction

In the twenty-first century, the energy sector is provided largely by cars, boats, trains, motorcycles and bicycles and varied by the population explosion, especially in urban areas [1], which attempt to replace individual means of travel. Their uses have caused constraints and limits as noise pollution, atmospheric pollution leading to global warming and respiratory diseases. For correcting the high use of fossil sources, they took as alternative solar energy but its intermittence recommends the use of storage systems, the most common of which are the storage batteries that is the most expensive component of a photovoltaic solar installation. In order to response to the high demands for current or power at engines start-up, we proposed the use of supercapacitors. J. Zhang et al. showed that Supercapacitors offer a suitable solution for mitigating voltage fluctuations, enabling smooth power transmission, and storing excess energy, especially in applications requiring a fast charge and discharge cycles [2]. Others authors searched a solution for regulating the voltage of a DC bus of the hybrid power system PV/Wind associated with storage devices. A hybrid energy storage system that combines batteries and super capacitors is good help because the batteries are employed to meet long-term energy requirements, while the integration of super capacitors allows to meet immediately the demand for instantaneous power [3]. And yet, other authors have shown supercapacitors combined with the fuel cell to provide power during acceleration, during transient phases and to recover braking energy [4].

Here, the high current demand during engine start-up leads to plate degradation and destruction of valve-regulated lead-acid (VRLA) batteries. To protect the batteries, they will be coupled with supercapacitors to form a hybrid storage system, where the battery provides continuous power in low sunlight and the supercapacitors generate instantaneous power to the load. The results showed that the hybrid storage system can achieve a higher specific power than the battery storage system [5].

In the literature, several authors have used supercapacitors in various applications. Some authors provided a comprehensive review of the use of supercapacitors in photovoltaic solar systems, analyzing their benefits for energy storage, their ability to supply energy during peak demand, and their role in improving the overall efficiency of photovoltaic systems [6]. In this article, Gualous et al. purpose some applications of supercapacitors, which are used firstly in starting a thermal engine and then in recovering braking energy from rail transport as storage. Finally, supercapacitors are applied to on-board storage, developed by Bombardier for the city of Mannheim [7].

A. Rufer et al. showed in their paper that the combination of super-capacitor and the battery provide energy in order to ensure the functioning of means of transport [8], while Kuperman et al. explained that battery-supercapacitor combination enables pulsed charging currents to be established [9].

Hence, in this paper, the latter will thus be integrated into solar photovoltaic water pumping systems in order to ensure the start-up of the motor pump set by supplying electricity in a very short time. In addition, in the event of energy limitation, the use of a supercapacitor associated with a battery makes it possible to extend the life of the latter by avoiding deep discharges during calls for power. In this study, we will discuss at first, we present the materials and methods, secondly, we will talk about the presentation and algorithm sizing of two water pumping solar PV systems : with battery only and another with battery and supercapacitors in the storage and we will finish by results and discussions of simulation.

2. Materials and Methods

Indeed, to describe the behavior of a hybrid solar photovoltaic water pumping system, in our study, we presented at first time a water pumping PV solar system with battery and secondly another water pumping system associated batteries and supercapacitors in the storage under Matlab Simulink. In our approach, we adopted as inputs, the meteorological data (temperature and solar radiation) of Koyli alpha, extracted from Widou station in Ferlo, Senegal. As a sizing process, we use the probabilistic approach, here, we took a day of August 2017 over a period of 24 hours to check the operation of the water pumping system. The mainly goal is to follow the operating of these two water pumping systems and to show the importance of supercapacitors in this water pumping system. In this work, we first present a stand-alone solar PV water pumping system and then a solar PV water pumping system whose storage system consists of batteries and supercapacitors. We present a first system consisting of 176 Aavid Solar 235-M 24V, panels, divided into two strings of 88 modules connected in parallel, 136 12V/10Ah lithium-ion batteries with a depth of discharge (DOD) of 85%, connected in series-parallel, and a second system with supercapacitor packs, consisting of 18 32-F, 2.7V cells, all connected in series. The operation of both systems is simulated using Matlab/Simulink. To perform these simulations, we use two sizing algorithms, which have as inputs hourly meteorological data on temperature and solar radiation from the village of Koyli Alpha, collected from the Widou station in Ferlo, Senegal. In our study, we adopt a probabilistic approach i.e. the use of hourly data of ambient temperature and solar radiation and use the day of August 1, 2017. Finally, we conclude with the results obtained from the simulation.

1. Presentation and sizing algorithm for a stand-alone solar PV water pumping system without supercapacitors

In this section, we work with a stand-alone solar PV water pumping system without supercapacitors. Therefore, we list the different productions (solar PV and batteries) and the discharge state of the batteries. The intermittent nature of the solar radiation justifies the main choice of batteries in the storage device used in this solar PV water pumping system. The latter consists of panels, a unidirectional DC-DC Boost converter, batteries, a bidirectional DC-DC converter, an inverter, a load (motor and pump). System supervision is provided by MPPT and P&O controllers.

Figure 1 presents a solar PV water pumping system without supercapacitors in the storage on Matlab/Simulink.

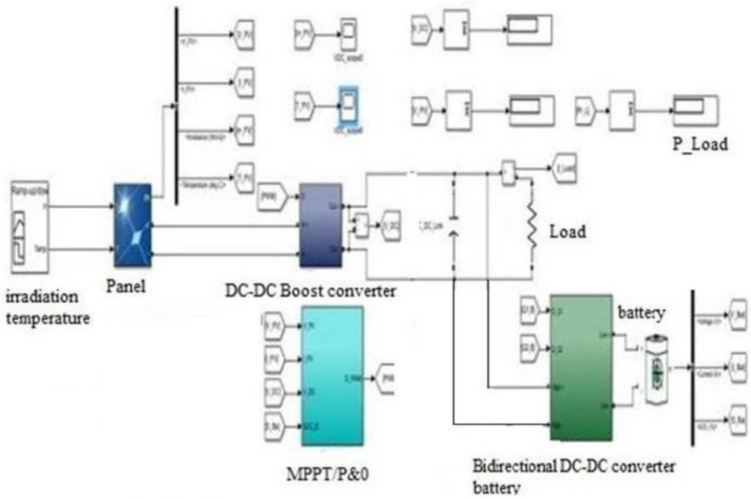

Figure 1: Presentation of a Solar PV water pumping system with battery under Matlab/Simulink

In order to satisfy the load demand, we purpose a sizing algorithm which calculates the solar PV power, the batteries power and the batteries' state of discharge during 24 hours. Figure 2 shows the sizing algorithm of a solar PV water pumping system with battery.

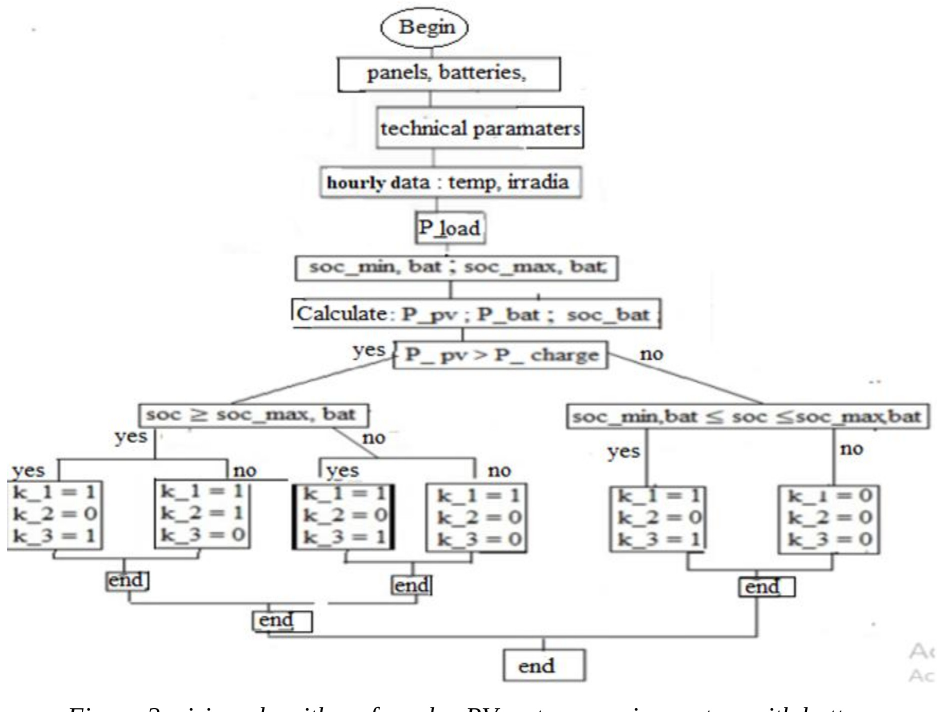

Figure 2: sizing algorithm of a solar PV water pumping system with battery

To describe this sizing algorithm, we focus on the PV array's output. In this case, two major conditions govern the control and operation of this solar PV water pumping system.

The power balance is given by equation (1)

$$P_{Load} = P_{PV} + P_{Bat} \quad (1)$$

P_{Load}: load power;

P_{PV}: Photovoltaic power;

P_{Bat} : Battery power;

We consider the first condition, when the PV power is greater than the load power, given by equation (2):

$$P_{PV} > P_{Load} \quad (2)$$

If this condition is met, the excess energy is used to charge the batteries, and the following condition occurs:

$$\mathrm{SOC} \geq \mathrm{SOC}_{\mathrm{max,\,bat}} \qquad (3)$$

If this condition is true, two sub conditions are required: charging and discharging.
The switches are in positions K1 = 1, K2 = 0 and K3 = 1. We observe a battery discharge, even though the battery's state of charge corresponds to the switch positions K1 = 1, K2 = 1 and K3 = 0.
When this condition is not met, a first scenario shows that the batteries are still in discharge mode and the panel is producing electricity. In this case, the switches are in positions K1 = 1, K2 = 0, and K3 = 1.
On the other hand, the batteries no longer function; only the panel continues to produce electricity and we are in positions K1 = 1, K2 = 0 and K3 = 0. When K1, K2, and K3 are in position 1, it means that the panel is producing electricity and the battery is in the charging and discharging states, respectively. When switches K1, K2 and K3 are in position 0, the panel no longer produces electricity and the batteries are completely shut down: neither charge nor discharge.
The second condition means when the PV power is lower than the load power, given by equation (4):

$$\mathrm{P}_{\mathrm{PV}} < \mathrm{P}_{\mathrm{Load}} \qquad (4)$$

If this condition is accepted, we obtained in equation (5):

$$\mathrm{SOC}_{\mathrm{min,\,bat}} \leq \mathrm{SOC} \leq \mathrm{SOC}_{\mathrm{max,\,bat}} \qquad (5)$$

If this battery protection condition is true, the panel supplies power to the load (K1 = 1) and the batteries discharge (K2 = 0 and K3 = 1). When the battery protection condition is not met, the system is completely shut down and the switches occupy positions K1 = 0; K2 = 0; and K3 = 0.
In this paper, the investigation of a hybrid PV–battery/supercapacitor system and active power control in MATLAB/Simulink for a new topology. Supercapacitors used in active PV power control will not have an extra price, because using in load side reduce the price of the storage system as has been proven. Also, using supercapacitors will reduce the prices in some extra aspects, such as by reducing battery aging and increasing efficiency. A new topology for HESS to share the PV power and to shave the PV peak power is proposed. The proposed passive HESS, which combined the PV module with MPPT and the supercapacitor module, was designed in MATLAB/Simulink. The simulation results show that this topology can be used for HESS to increase efficiency and can be applied experimentally [10].

2. Presentation and sizing algorithm for a solar PV water pumping system with supercapacitors

In the next section, we present the solar photovoltaic water pumping system whose storage consists of batteries and supercapacitors. It consists also panels, two bidirectional DC-DC Boost converter, an inverter, a load (motor and pump). System supervision is provided by MPPT and P&O controllers.

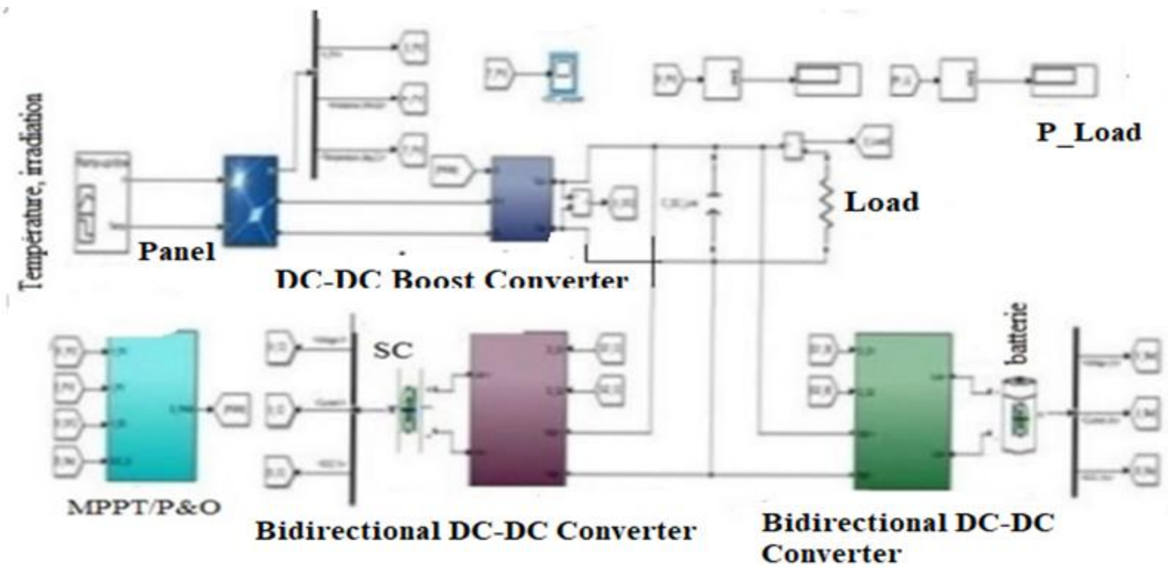

Figure 3: Presentation of a Solar PV water pumping system with battery and supercapacitors under Matlab/Simulink

In order to satisfy the load demand, we purpose a sizing algorithm which calculates the solar PV power, the batteries power, the load variation and state of charge or discharge during 24 hours. Figure 4 shows the sizing algorithm of a water pumping PV solar system with battery.

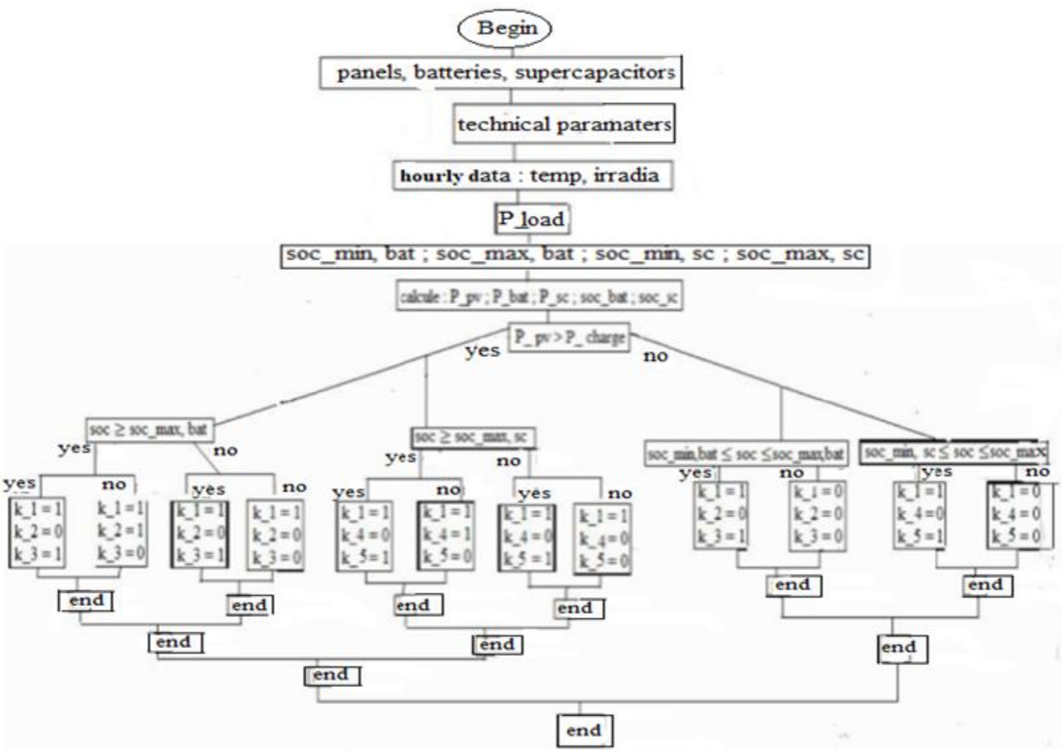

Figure 4: sizing algorithm of a solar PV water pumping system with battery and supercapacitors

Here, we adopt a sizing algorithm allowed to calculate the different solar PV and battery powers, respectively, and the variation of discharge states of the battery over 24 hours. The operation's control of solar PV water pumping system is MPPT and PO controllers, we keep in storage batteries and supercapacitors. To ensure proper operation, we are interested in the power balance. This relates the charging power to the sum of the photovoltaic, battery, and supercapacitor power. Thus, we seek to satisfy the charging demand using the solar photovoltaic power and the battery and supercapacitor power.

The power balance is given by equation (6).

$$P_{Load} = P_{PV} + P_{Bat} + P_{SC} \qquad (6)$$

P_{Load}: load power;

P_{PV}: Photovoltaic power;

P_{Bat} : Battery power;

P_{SC}: Supercapacitor power.

Calculating the sizes of photovoltaic panels, batteries, and supercapacitors allows us to find the energy difference between the photovoltaic solar production and the load (motor pump).

This difference is explained by the inequalities given by equations 7 and 10.

In order to verify the operation of a solar PV water pumping system with supercapacitors and batteries in storage, we present the following condition from equation (7):

The operation of a water pumping solar PV hybrid system are described in the following case:

The PV power is greater than the load power, given by equation (2):

$$P_{PV} > P_{Load} \qquad (7)$$

The power excess allowed to charge batteries and supercapacitors and the photovoltaic panels continue to supply the motor pump group. We have these conditions:

If this condition is met, the excess energy is used to charge the batteries, and the following condition occurs:

$$\mathrm{SOC} \geq \mathrm{SOC}_{\text{max, bat}} \quad (8)$$

$$\mathrm{SOC} \geq \mathrm{SOC}_{\text{max, SC}} \quad (9)$$

And two scenarios are necessary. When the first condition is true, the panel operates the load (K=1) and the batteries (K2=0 and K3=1) and supercapacitors (K4=0 and K5=1) are in discharge mode. Otherwise, the switching is positioned in battery charging mode (K2=1 and K3=0) and supercapacitors (K4=1 and K5=0).

If the condition of the state of charge of the battery and the supercapacitor is not verified and the panel still produces (K=1), we had two possibilities:

In charging mode, the storage devices occupy the points K2=0 and K3=1 for the batteries and K4=0 and K5=1 for the supercapacitors. When they discharge the switches are all at K2=0 and K3=0 for the batteries and K4=0 and K5=0 for the supercapacitors, which means that these two storage systems are neither charged nor discharged.

If this first sub condition is not met and the panel continues production when (K = 1), we have two possibilities: when the switches occupy positions K2 = 0 and (K3 = 1) for the batteries and (K4 = 0 and K5 = 1) for the supercapacitors, we are in discharging mode. In the case where the switches are in positions K2 = 0 and K3 = 0 for the batteries; and K4 = 0 and K5 = 0 for the supercapacitors, we note that the power supply is provided only by the panels and that these two storage devices are neither charged nor discharged.

When solar power is unable to meet the charging demand, the condition is given

$$P_{\text{PV}} < P_{\text{Load}} \quad (10)$$

If this condition is accepted, we will subject the batteries and supercapacitors to between the minimum and maximum charging values:

$$\mathrm{SOC}_{\text{min, bat}} \leq \mathrm{SOC} \leq \mathrm{SOC}_{\text{max, bat}} \quad (11)$$

$$\mathrm{SOC}_{\text{min, SC}} \leq \mathrm{SOC} \leq \mathrm{SOC}_{\text{max, SC}} \quad (12)$$

To better manage the operation of a water pumping solar PV hybrid system, we are interested in the following case. If the condition of the protection state of the batteries and the supercapacitors is respected, the panel supplies the load in an unsatisfactory manner and the storage sources are in discharge mode (K2=0 and K3=1) and (K4=0 and K5=1). We can meet a situation that the capacity of the batteries or the supercapacitors are equal to the minimum required, we would have a load loss and a probability of loss of load. By account, else we remarked in storage devices can no charge, no discharge and the system are stopped its operating (K1 =0, K2 =0, K3=0, K4 =0 and K5 =0).

When the first sub condition is true, the panel operates the motor pump because the switch (K = 1) is in closing mode while the batteries (K2 = 0 and K3 = 1) and the supercapacitors (K4 = 0 and K5 = 1) are in discharging mode. Otherwise, the switch is positioned in charging mode for the batteries (K2 = 1 and K3 = 0); and for the supercapacitors (K4 = 1 and K5 = 0).

If this sub condition of the protection status of the batteries and supercapacitors is met, the panel supplies the load unsatisfactorily, and the latter are in discharge mode K2 = 0 and K3 = 1 and K4 = 0 and K5 = 1. We can thus reach the situation where the capacities of the batteries and supercapacitors are equal to the minimum required, and we observe a loss of charge. By contrast, if the sub condition is not met, we note that these storage devices can no longer charge or discharge, and the panels no longer produce power. Therefore, the switches are at levels K1 = 0, K2 = 0, K3 = 0, K4 = 0, and K5 = 0. The simulation of the operation of the two systems generates the following results.

This section presents the results obtained from the simulation of the operation of two solar PV water pumping systems, respectively without and with supercapacitors. Figure 5 summarizes the variation in load power in a stand-alone solar PV water pumping system with and without supercapacitors.

3. Results and discussions

The figure 5 summarized the solar productions in a stand-alone solar PV water pumping system without supercapacitors and a stand-alone solar PV water pumping system with supercapacitors in the storage.

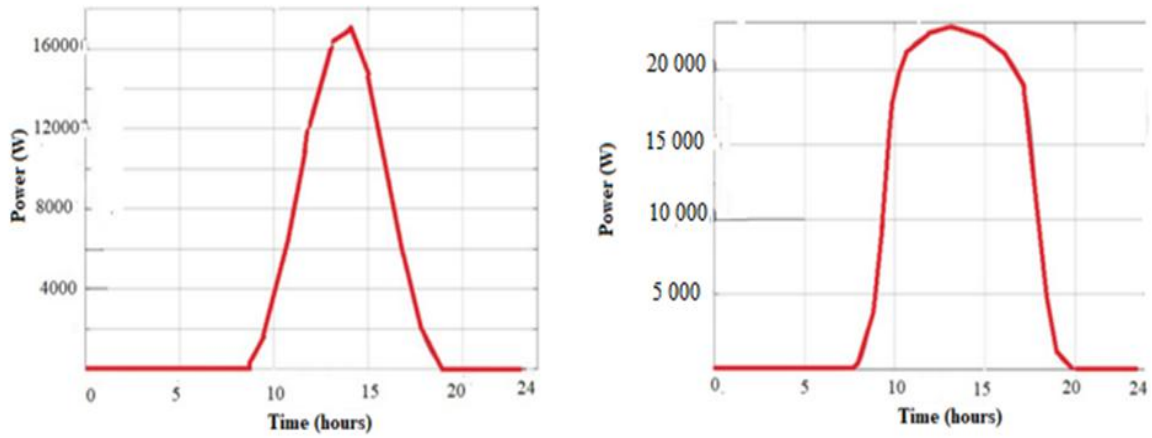

Figure 5 (a): Solar production in an autonomous water pumping system without supercapacitors. (b) Solar production in an autonomous water pumping system with supercapacitors.

We can conclude that the motor's water capacity is a function of the water capacity, which is correlated with sunlight.

By analyzing figure (a) without supercapacitors in the storage, we noted that the load variation depends on the daily path of the sun. Sunshine varies between 9 a.m. and 7 p.m., and the highest PV production, 18.2 kWp, is recorded at 2 p.m. After 7 p.m., we note that the PV production cancels out because it is dark, hence the absence of the solar source. This intermittent solar activity necessitated the use of a storage device to ensure a continuous supply of water to the pumping system. Furthermore, figure (b) provides information on the PV production in the autonomous solar PV water pumping system with supercapacitors. This PV production is used by the load, which varies depending on sunlight of the study site. Solar radiation varied from 8 a.m. to 7 p.m. and generated a maximum solar PV power equaled to 23 kWp and the solar production is equaled to zero between 8 p.m. to 12 p.m and 12 p.m to 8 a.m. The solar PV power is high because the contribution of the supercapacitors favored this increase at the DC bus input.

Figure 6 presents the power share of batteries in a solar PV pumping system with and without supercapacitors

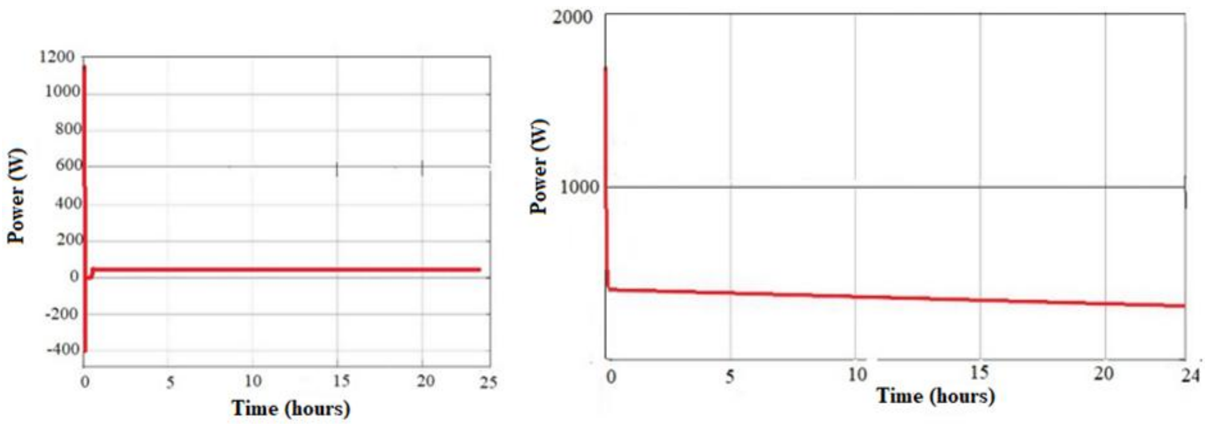

Figure 6 (a): Battery production in a stand-alone solar PV water pumping system without supercapacitors. (b) Battery production in a stand-alone solar PV water pumping system with supercapacitors.

In order to solve the demand of water, we used batteries for supply the motor. The integration of batteries in this system was given an autonomous system. Analysis of figure (a) revealed a high level of battery energy use. They ensured the load supply during night and days without sun. At the startup of motor, the batteries brought an important response equaled to 1,155 W and decreased until 85 W at same time. The batteries' production varied slowly between 1 am to 12 pm. This low battery share justifies powering the engine from the battery's storage. This lowest variation means the poor part of batteries during sunniest moments of the day. The negative power means the state of charge of batteries. Yee et al. showed in their work that the number of batteries is used in a system with hybrid energy storage system has lower than a system of batteries only. It is good for the environment as the supercapacitors are more environmental-friendly as most of the material composition of supercapacitor can be more biodegradable as compared to that of battery [11].

As for figure (b), the batteries and supercapacitors are the main storage sources met in this hybrid system. At the start 'up of motor, the batteries brought an important response equaled to 1,760W and decreased quickly until 250W from 00 O'clock to 11 p.m., these low values between 250W and 180 W traduces the low part of batteries during sunniest periods and also supercapacitors presence. A. Rufer et al. showed a simulation for a real elevator with a car weight of 720 kg, balanced with a counter weight of 1,440 kg and the car was loaded with 1,400 kg. The energy amount needed for the 10 floor up-run is equal to 220 kJ while the maximum power demand is equal to approximately 33 kW. The sizing of supercapacitors bank is based on the result of the needed energy amount, at first we are looking for that a supercapacitor tank is able to deliver the maximum needed instantaneous power, reached at the end of the acceleration phase of the up-run. Taking a maximum value of the current in each 1,800 Farads supercapacitors, the design of the tank leads to an oversized maximum energy capacity of 675 kJ. That value corresponds to a global capacity of 135 Farads under a full load voltage of 100V. The array of the tank is a total of 120 elements corresponding to 10 floors up-run causes consequently a voltage decrease down to 82 Volts, extracting so 67% of the energy capacity [12].

Figure 7 presents the discharge state of battery in two Solar PV water pumping systems supercapacitors

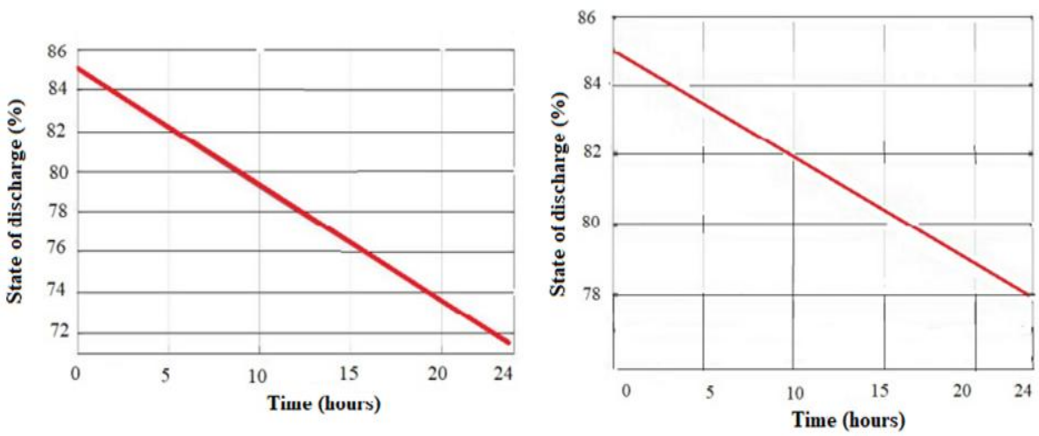

Figure 7 (a): Battery discharge state in a stand-alone solar PV water pumping system without supercapacitors. (b) Battery discharge state in a stand-alone solar PV water pumping system with supercapacitors.

Figure (a) shows the daily profile of the battery discharge state. Here, we observe a decrease in the energy capacity stored in the battery over 24 hours. The depth of discharge is set at 15% by the manufacturer, or 85% of the maximum charge level. At midnight, the battery charge level is at 85% and decreases to 71% over 24 hours. The lost energy and the contribution of the batteries explain why PV production no longer fully meets the load demand. Using Figure (b), we note that the battery status in a stand-alone solar PV water pumping system with supercapacitors varied over 24 hours Upon engine start-up, the battery level is above 85% and decreases to 78% over 24 hours. This low battery discharge is due to the presence of supercapacitors, which reduce the battery contribution and lead to an increase in battery life and cycle count. While Q. Hassan et al., in their research study used a supercapacitor module as a fast-response energy storage in order to improve energy self-consumption and self-sufficiency for renewable energy systems applications. The simulation results demonstrated that the use of the five supercapacitor modules ensured the rapid peaks of electrical load and provided an increase annual energy self-consumption and self-sufficiency varied respectively between 21.75% to 28.74% and 28.09% to 40.77% [13].

J. Kim et al. also compare the estimated battery lifetime when the battery is in idle state and the battery is used without and with a booster. The battery in idle state with 25°C is the reference parameter of each cases of batteries lifetime. A lifetime of 100% denotes the full 15 years of shelf life, while 71.2% means that the battery capacity is reduced to 80% of its initial value after 10.7 years. Therefore, we first estimate the lifetime of batter

in idle state with 30°C to distinguish the battery aging due to temperature and the discharging and charging. The lifetime decreases as 71.1% of the baseline when the battery is stored in 30 °C using the laptop without a booster makes it worse and reduces the lifetime as 31.4%. The lifetime increases as 46.8% if we rely on the booster with 10 mF supercapacitor which is used. If we use the optimal booster designed by the proposed methodology with 17.5 mF supercapacitor, 4–20 V 30 °C and the lifetime of battery is enhanced as 49.6% [14]
Finally, Figure 8 shows the daily variation in supercapacitor production in a stand-alone solar PV water pumping system with supercapacitors.

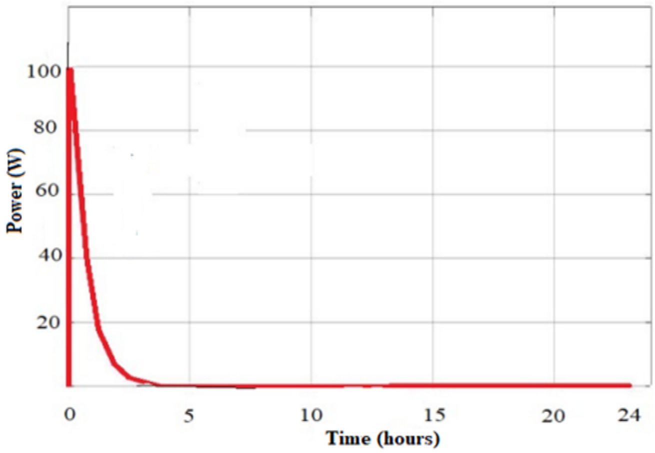

Figure 8: Daily variation in supercapacitor production in a stand-alone solar PV water pumping system

In this solar PV water pumping system using batteries and supercapacitors in storage, we note a contribution from supercapacitors to meet the motor power demand during startup. In the literature, Mousavi et al., focused their discuss in the manner that supercapacitors can be used to improve the performance of solar systems, particularly in situations where fluctuations in solar production can lead to unstable energy supply [15]. The study of Jie Zhang et al. showed where supercapacitors can support batteries in compensating for the imbalance between abundant renewable energy productions of sustainable energy systems thanks to their competitive power density [2]. Currently, we record a supercapacitor power value of 110 W, which decreases from 3 a.m. to midnight.

4. Conclusion

The main objective of this study, carried out on the Koyli Alpha site, is to make a comparative study between an autonomous photovoltaic solar water pumping system without and with supercapacitors in order to find an optimal response to the start-up of the solar pump. The study used hourly meteorological data and the existing solar pumping system first used the storage batteries and finally supercapacitors. During the start-up, the solar pump drew all its energy from the batteries and the consequence would be a reduction in their lifespan. Thus, we have associated supercapacitor packs with the batteries in order to ensure the good functioning of the boreholes and to reduce the excessive use of the batteries. With Simulink / Matlab software, we observed a strong power response from the supercapacitors and a considerable reduction in the supply from the batteries to the DC Bus. This power imbalance is more advantageous for batteries with 7% power gain on its total capacity. The power response and importance of supercapacitors will be the subject of a future application on solar home systems such as refrigerators and solar mills.

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