DOI: 10.17587/mau.20.669-676

**M. Ali Ben Fathallah**[1,2], PhD Student, mohamed-benfathallah@hotmail.fr,
**A. Ben Othman**[1,3], PhD, afef@benothman.de, **M. Besbes**[1,2], Professor, mongi.besbes@gmail.com,
[1] Robotics, Informatics and Complex Systems (RISC), National School of Engineers of Tunis,
University of Tunis El Manar, Tunis,
[2] Higher Institute of Information and Communication Technologies, University of Carthage, Tunis,
[3] National School of Engineers of Carthage, University of Carthage, Tunis

*Corresponding author*: **Ali Ben Fathallah Mohamed,** PhD Student,
Robotics, Informatics and Complex Systems (RISC), National School of Engineers of Tunis,
University of Tunis El Manar, Tunis, Tunisia, e-mail: mohamed-benfathallah@hotmail.fr

*Accepted on June 06, 2019*

# Stabilizing a DC Motor Speed of Photovoltaic Pumping System Using a Super Capacitor and Fuzzy Logic Controller

***Abstract***

*In this paper, two issues are discussed in a PV pumping system. Firstly, an evaluation of super capacitor is studied to reassure the storage of electrical energy and solve the intermittence problem of photovoltaic energy production in dark periods. Secondly, a fuzzy logic controller (FLC) is proposed to stabilize, on the one hand, the DC motor speed around a preferred level by the control of duty cycle of DC buck boost converter. On the other hand, FLC serves to control the charge and discharge of super capacitor according to the sunlight levels and its state of charge. In this framework, a complete photovoltaic pumping system model is simulated in MATLAB Simulink to discuss the run results at different levels of sunshine.*

***Keywords:*** *photovoltaic pumping system, super capacitor, fuzzy logic controller, DC buck boost converter, DC motor speed, state of charge*

For citation:

**Ali Ben Fathallah M., Ben Othman A., Besbes M.** Stabilizing a DC Motor Speed of Photovoltaic Pumping System Using a Super Capacitor and Fuzzy Logic Controller, *Mekhatronica, Avtomatizatsiya, Upravlenie*, 2019, vol. 20, no. 11, pp. 669—676.

УДК 681.51

DOI: 10.17587/mau.20.669-676

**М. Али Бен Фатхаллах**[1,2], аспирант, mohamed-benfathallah@hotmail.fr,
**А. Бен Отман**[1,3], PhD, afef@benothman.de, **М. Бесбес**[1,2], проф., mongi.besbes@gmail.com,
[1] Лаборатория робототехники, информатики и сложных систем, Национальная инженерная школа Туниса,
Университет Тунис-Аль-Манар, г. Тунис, Тунис,
[2] Институт информационно-коммуникационных технологий, Университет Карфагена, г. Тунис, Тунис,
[3] Национальная инженерная школа, Университет Карфагена, г. Тунис, Тунис

# Стабилизация двигателя постоянного тока в фотоэлектрической насосной системе с помощью суперконденсатора и нечеткого логического контроллера

*В данной работе обсуждаются две проблемы, связанные с фотоэлектрической насосной системой. Во-первых, проводится анализ суперконсенсатора, направленный на обеспечение хранения электроэнергии и разрешение проблем, связанных с отсутствием производства фотоэлектрической энергии в темное время суток. Во-вторых, предложено использовать в системе нечеткий логический контроллер. С одной стороны, он предназначен для стабилизации частоты вращения двигателя постоянного тока вблизи предпочтительного значения за счет управления режимом работы комбинированного преобразователя постоянного тока. С другой стороны, этот контроллер служит для управления зарядкой и разрядкой суперконденсатора в соответствии с уровнем солнечного освещения и уровнем заряда конденсатора. Полная модель фотоэлектрической насосной системы исследуется в MATLAB Simulink. Обсуждаются результаты моделирования при разных уровнях освещения.*

***Ключевые слова:*** *насосная фотоэлектрическая система, суперконденсатор, нечеткий логический контроллер, комбинированный преобразователь постоянного тока, частота вращения двигателя постоянного тока, состояние заряда*

## Introduction

The increase of oil prices and electricity billing, the abandonment of the silicon material and the sunshine of almost all the planet, are major factors leading to seek new energy sources such as photovoltaic electricity, free and independent of any other source of energy. This is why scientific research is reacting to improve the quality of photovoltaic energy to ensure consumer performance for the user [28, 29], and having a good knowledge of the basic solar components, including Direct Normal Irradiation (DNI),Global Horizontal Irradiation (GHI), is greatly significant to photovoltaic system (PV) projects. Moreover, the applicability of solar energy in area such as in the south of Tunisia can be an answer to the overgrowing problems of depleting fossil fuel supplies and $CO_2$ emissions in Tunisia [30, 31].

Several applications are powered by photovoltaic energy, such as satellites, electric cars, street lighting, boilers, and home installations. This paper represents a study of the photovoltaic water pumping system, which is still an essential function for living beings. This function requires an energy storage system to remedy the intermittent problem of system operation following the absence of sunshine during nights and cloudy days or in case of maintenance.

Despite the maturity of their technologies and their low cost, the number of cycles of conventional batteries is very limited, moreover these storage devices are affected by the memory impact that decrease their performance if they are not completely discharged before being recharged again [1].

Since 1978, super capacitors have appeared to perform the memory function in some electrical devices, such as VCRs and cameras. They were also exploited in 1990s to power toys and household equipment, and developed recently in electric vehicles and energy sources with higher storage capacities [2]. These ideal electrical properties have resulted in the rapid growth in the market of this element.

Indeed, the super capacitor is characterized by its long life span of up to 15 years, a cyclability that can exceed 20000 cycles of charge and discharge, a very high power density up to 18 KW/Kg and has no risk of explosion or thermal runaway [3, 23, 22]. All these advantages are the benefits of its new structure consisting of an electrolyte placed between two porous electrodes. The porosity of the electrodes offered a wider space for moving to a larger amount of charged ions, which provides an enormously high storage capacity compared to conventional batteries [4].

Experimental tests and simulations in MATLAB Simulink allowed to model the super capacitor by linear circuit with three branches RC, each branch of which describes the internal phenomena of the super capacitor during the phases of charge, discharge and rest [5, 23, 24].

Thanks to its efficiency and its simplicity compared to other models, the three branches RC model is taken into account, in this paper, to be implemented in the PV pumping system and simulated in Matlab Simulink in order to validate the storage performance by the super capacitor.

The pumping function can be disturbed by the accumulation of limestone, sand and pebbles at the pump, which reduces the stability of the pumping motor speed. Therefore, the control of the pumping motor voltage is unavoidable, and it is ensured by the intermediate of a DC buck boost converter placed between the power supply and the DC motor, which allows to increase or decrease the DC motor voltage to reach the nominal speed, playing on the duty cycle value by a sufficiently robust control technique.

Invented in 1965 by professor of mathematics L. A. Zadeh [20], the fuzzy logic controller has been used in several applications. Indeed, D. K. Grover has implemented the fuzzy logic controller for image processing, noise cancellation and the control of water level and shower temperature. He has thus demonstrated his simplicity [19]. This method has invaded the field of biomedical informatics and life sciences [18]. It has also been used to control automotive suspension systems [16], and the power of nuclear reactors [17]. In addition, FLC has demonstrated an intelligent behavior in the field of robotics for obstacle avoidance and line tracking [15].

The comparative studies that were analyzed between fuzzy logic and the neural network controller, clearly affirmed the performance and accuracy of the fuzzy logic to follow the reference, and its ability to model inaccurate knowledge [10, 12, 13].

In addition, K. V. Chate, O. E. Prado and C. F. Rengifo demonstrated that the fuzzy logic controller allows a smaller error deviation compared to the LQR and PID controllers, while ensuring a large equilibrium point of attraction region without wasting energy [14]. In terms of response time, this control method is faster compared to the PI controller and can immediately reach the reference with lower overruns [7, 11].

The fuzzy logic controller is also favored by its dynamic behavior and the self-tuning of its gain, which is the reason that allows stability and robustness of control against unexpected variations in machine parameters [9, 10].

Unlike the PID controllers, the fuzzy logic controller does not require any mathematical model development of the system, it satisfies the non-linear criteria in all operating ranges, which reflects its importance for controlling the complex systems [6].

P. R. Komar and S. L. V. Sravan Kumar have carried out experimental studies demonstrating that the ripple of the output voltage exceeds 3 V for Flyback converter controlled by PID controller, however this value decreases to 0.2 V and the power factor of Flyback converter reaches 70.07 % using the fuzzy logic controller [8].

All these advantages are sufficiently convincing to choose the fuzzy logic controller to control, on the one hand, the MOSFET integrated in the DC buck boost converter in order to vary its duty cycle and follow the reference speed of DC pumping motor in all the sunning conditions. On the other hand, the charge and discharge control of the super capacitor is accomplished through the fuzzy logic controller according to the level of sunlight and its state of charge.

In this context, this paper presents, in the first part, a modeling on Matlab Simulink of super capacitor by the three branches RC model, in the three branches RC model. In the second part a description of the implementation of fuzzy logic controller using Matlab Simulink to follow the state of charge of super capacitor and to vary the duty cycle of DC back boost converter in order to maintain the stability of DC Motor speed in a PV pumping system. Finally simulation results are discussed.

## Model of PV pumping system

The PV pumping model, as shown in Fig. 1, is achieved through MATLAB Simulink. It consists of a photovoltaic panel model representing the main power supply of the system, a three-branch RC model of super capacitor to ensure the continuity of system operation, and two fuzzy logic controllers, the first of which controls the loading or super capacitor discharge according to its state of charge, while the second controls the duty cycle of DC buck boost converter in order to maintain DC motor speed in its stable state.

## Three branch RC model of Super capacitor

To model the super capacitor, it is necessary to know its chemical composition, understand its functioning and visualize the internal phenomena which can appear during the phases of charge, discharge and rest.

Indeed, the basic structure of this storage device is composed of an ionic electrolyte placed between two porous electrodes ensuring a larger space for the displacement of the ions carrying the charge [23, 27]. There is a nonlinear relationship between super capacitor capacitance and the surface of the material, a consequence of the heterogeneity of the electrodes and the variation of the pore depths. Therefore the super capacitor model consists mainly of a variable capacitance [4].

Zubieta and Bonert have proved, through experimental tests, the appearance of charge redistribu-

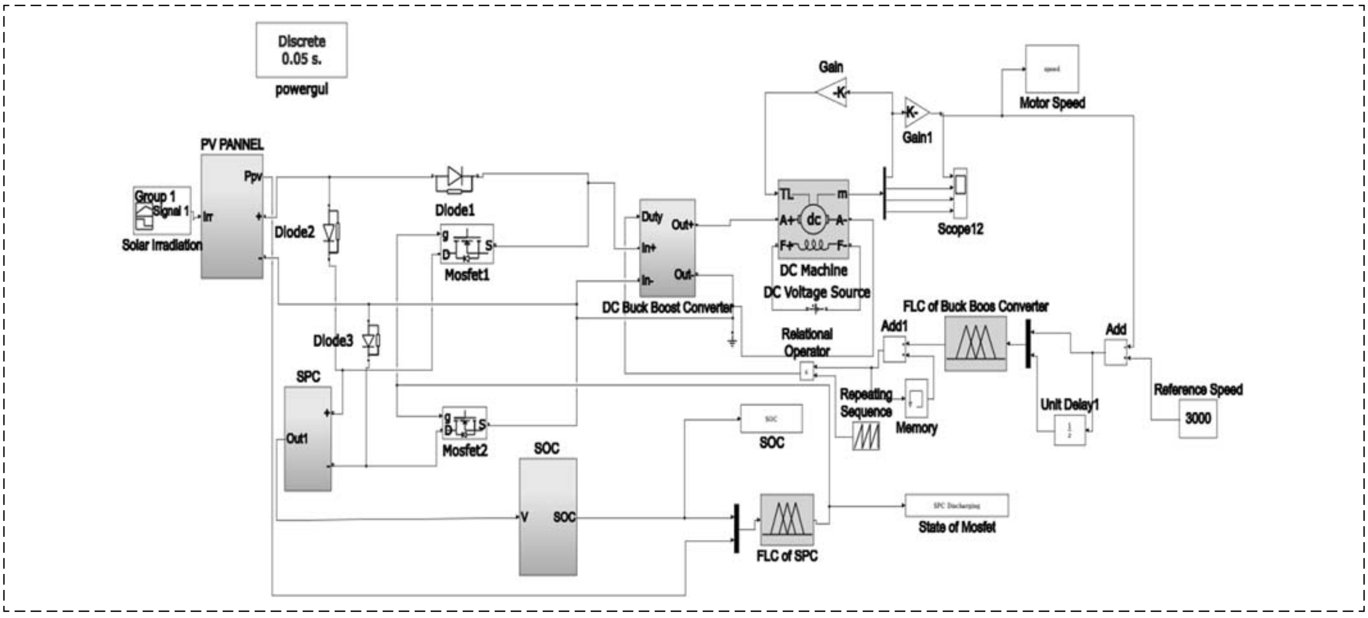

Fig. 1. PV pumping system model in MATLAB Simulink

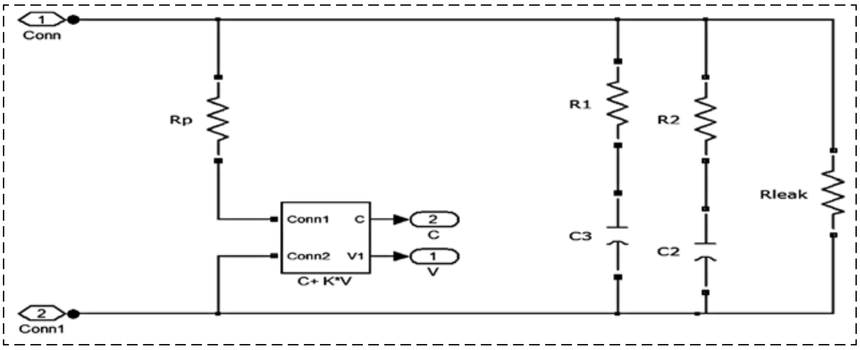


**Fig. 2. Super capacitor Model in MATLAB Simulink**

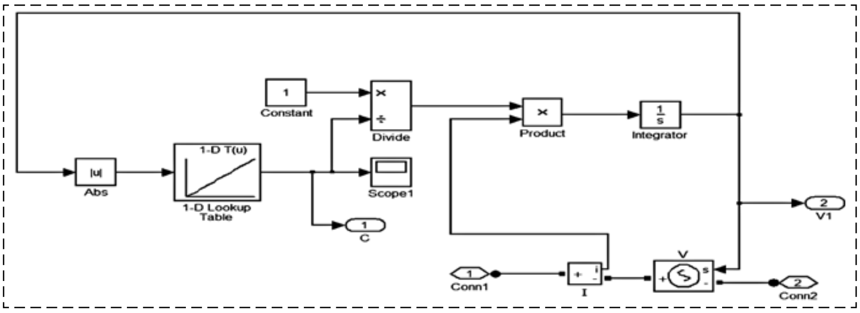


**Fig. 3. Linearity of the super capacitor capacity according to the charging voltage**

tion and self-discharge phenomena during the rest phase of the super capacitor, and this is explained by the mobility of charged ions. To simulate these phenomena, an RC circuit can be included in the super capacitor model [5]. The nature and electrochemical structure of the ionic electrolyte is also modeled by a second RC circuit [4].

This three branch RC model consists, as shown in Fig. 2, of a fast branch consisting of a series resistor with a variable capacitance as a function of the charging voltage, and two branches, medium-term and long-term, to describe the effect of redistribution of charge as a function of the duration of the rest phase. The presence of leakage resistance connected in parallel illustrates the phenomenon of self-discharge [21, 23].

The super capacitor capacity is expressed as a function of the charging voltage by the following linear relationship:

$$C = C_0 + KV. \qquad (1)$$

$C_0$ is the base capacitance of super capacitor, K is the voltage-dependent capacitance in F/V. His model on MATLAB Simulink is shown in Fig. 3.

The state of charge (SOC) of super condenser is a very important parameter, it is defined by the power amount available on the super capacitor, and given by the ration of the current capacity $Q$ to the nominal capacity $Q_n$ [25, 26]:

$$SOC = \frac{Q}{Q_n}. \qquad (2)$$

Which gives the following equation:

$$SOC = \frac{(C_0 + KV)V}{C_n V_n}. \qquad (3)$$

From the value of this parameter, the super capacitor is controlled during the charge or discharge cycles.

## Model of DC buck boost converter

The use of a DC-DC converter allows generation of an output voltage at the desired level. Knowing that the DC buck converter makes it possible to lower the output voltage, and the DC boost converter makes it possible to raise the output voltage, the DC buck boost converter is implemented in the PV pumping system to play dual roles: on the one hand it plays the role of DC buck converter if the supply voltage is higher than the pumping motor voltage, on the other hand it plays the role of DC boost converter if the supply voltage is lower than the pumping motor voltage.

The choice of conversion mode of this type of converter is ensured by the variation of its duty ratio $D$ between 0 and 1, this parameter makes it possible to obtain the relationship between the output voltage and the input voltage as indicated by following equation:

$$V_s = \frac{D}{1 - D} V_e. \qquad (4)$$

As shown in Fig. 4, the DC buck boost converter is compiled of a power MOSFET transistor used as a controllable switch, a diode, a filter capacitor Cc and an inductance Lc.

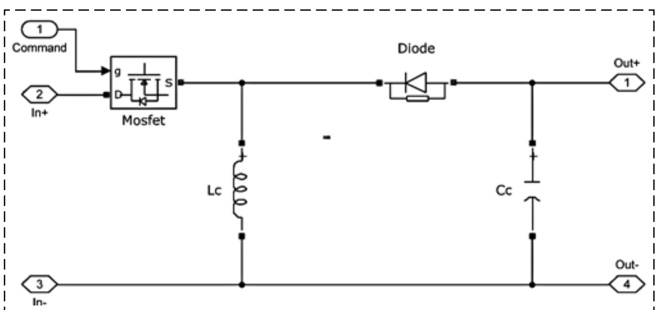


**Fig. 4. DC Buck Boost converter model in MATLAB Simulink**

When the MOSFET is in the on state, the input source supplies the energy to the inductor Lc, which will be conducted through the diode, during MOSFET blocking, to be discharged into the capacitor and the load.

The value of capacitor of buck boost converter is obtained by the following expression:

$$Cc = \frac{U_e}{\Delta U_s f Rc} \frac{D^2}{1 - D}. \quad (5)$$

$U_e$ is the input source voltage, $\Delta U_s$ is the ripple of the output voltage, $f$ is the MOSFET switching frequency, and $D$ is the duty cycle of $DC$ buck boost converter.

The inductance of buck boost converter is expressed as a function of the current ripple $\Delta I_{lc}$ that passes through it:

$$Lc = \frac{U_e}{\Delta I_{lc} f} D. \quad (6)$$

In order to minimize the current and voltage output ripple, the maximum duty cycle value is taken into account in the calculation of the buck boost converter parameters.

## Fuzzy logic controller

This part represents the fuzzy logic controller used to control, on the one hand, charging or discharging super capacitor according to its state of charge, on the other hand to stabilize pumping motor at its nominal speed.

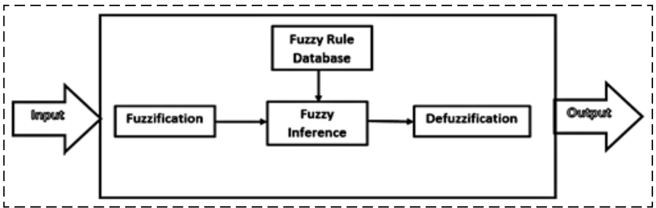


**Fig. 5. Flowchart of working principle of Mamdani method**

Without recourse to mathematical models and using only a human experience, the fuzzy logic controller is incorporated, as show in Fig. 5, in the form of three main steps: the fuzzification step, the inference step and the defuzzification step.

- **Fuzzification step**

It is the projection of real physical variables on fuzzy sets characterizing the linguistic values taken by these variables, according to a definite membership function [32].

The membership functions follow an arbitrarily chosen form (triangular, trapezoidal, exponential, Gaussian ...). Triangular shapes are used in this work to facilitate programming. As for the number of membership functions, it is usually odd because they are distributed around an average value.

- **Fuzzy inference**

It relies on the use of an implication operator to evaluate the truth degree of a rule R of the form "If Condition 1 and Condition 2 Then Conclusion" [14]. This allows the quantification of the strength of the connection between the condition and the conclusion of the rule.

- **Defuzzification step**

The defuzzification step consists in transforming the fuzzy set resulting from the aggregation of the rules into a precise control quantity [14, 32].

The fuzzy logic controller is used for the decision making of super capacitor charging or discharging, and maintaining the pumping motor speed throughout its nominal value.

## Super capacitor charge and discharge control

The decision of super capacitor charging or discharging depends on its state of charge and on the solar irradiation.

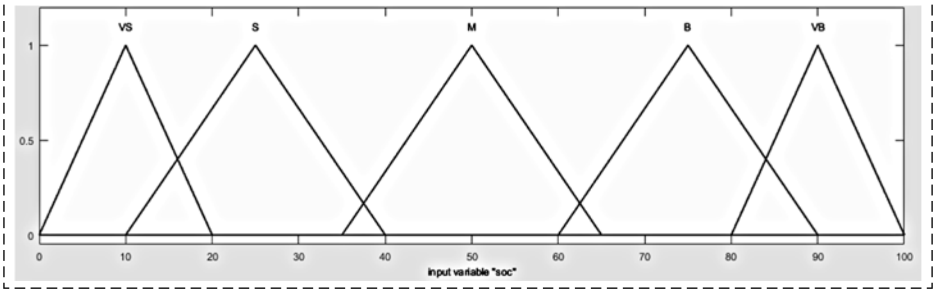


**Fig. 6. Fuzzy membership function of state of charge of super capacitor**

As shown in Fig. 6, the state of charge of super capacitor is classified into five linguistic variables: Very Small (VS), Small (S), Medium (M), Big (B) and Very Big (VB).

The solar irradiation classified into five linguistic variables: Small (S), Zero (Z) and Big (B): Very Small (VS), Small (S), Medium (M), Big (B)

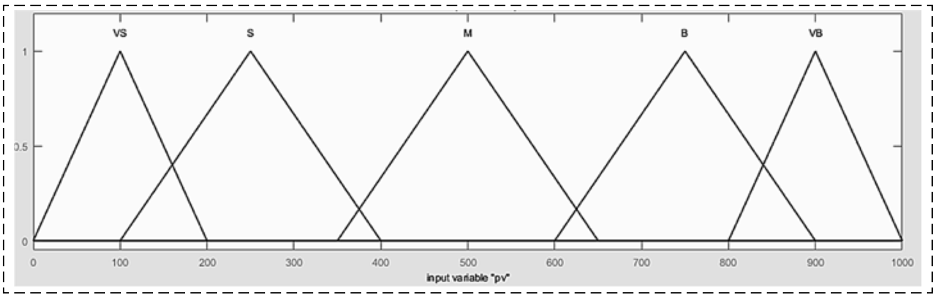


**Fig. 7. Fuzzy membership function of solar irradiation**

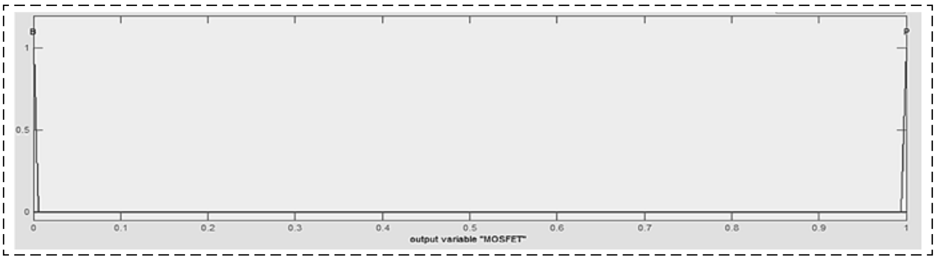


**Fig. 8. Fuzzy membership function of MOSFET state**

Table 1

**Rule Base of charging discharging control by fuzzy logic controller**

| SOC | pv | VS | S | M | B | VB |
|---|---|---|---|---|---|---|
| VS | | B | P | P | P | P |
| S | | B | P | P | P | P |
| M | MOSFET | B | B | P | P | B |
| B | | B | B | B | P | B |
| VB | | B | B | B | B | B |

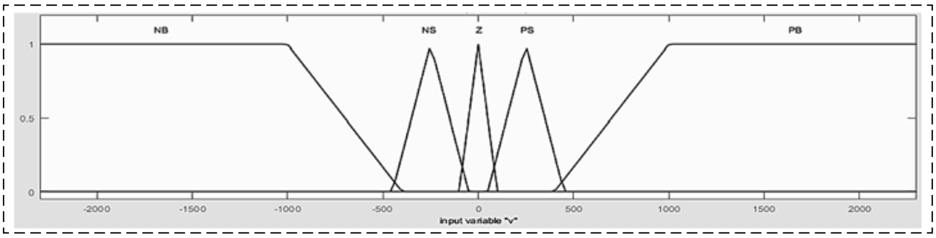


**Fig. 9. Fuzzy membership function of difference between motor speed and reference**

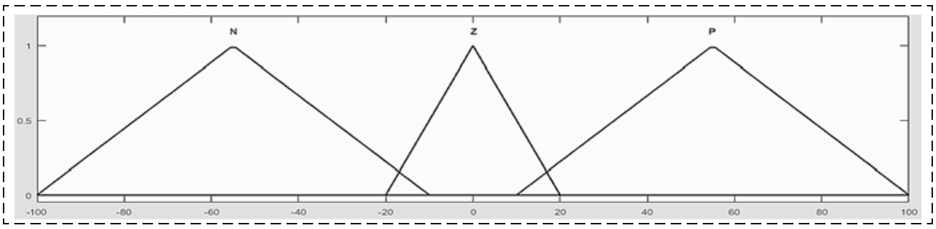


**Fig. 10. Fuzzy membership function of motor speed variation**

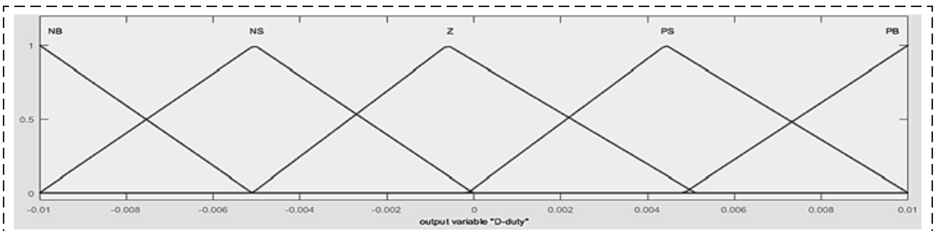


**Fig. 11. Fuzzy membership function of duty cycle of DC buck boost converter**

and Very Big (VB). Here membership function is shown in Fig. 7.

The fuzzy logic controller output represents the setting in 1 (P) or in zero (B) of MOSFET linking the super capacitor to the pump motor. See that the output is a Boolean variable (0 or 1), the intersection between the variables input is avoided to ensure control accuracy of the MOSFET. The membership function of the MOSFET state is represented by Fig. 8.

Table 1 represents the rules base of fuzzy logic controller.

## DC pumping motor speed control

To maintain the pumping motor speed close at its nominal value, a comparison is made between the measured and the reference speed. This comparison represents the fuzzy logic controller input, it is classified, as shown in Fig. 9, into five linguistic variables: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB).

The second input of fuzzy logic controller is the sign of the variation of the pumping motor speed, it is classified into three linguistic variables: Negative (N), Zero (Z) and Positive (P). Here membership function is shown in Fig. 10.

The duty cycle of DC buck boost converter is controlled by the fuzzy logic controller, it is classified into five linguistic variables: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB). Fig. 11 shows here membership function.

Table 2

**Rules base of DC motor speed control by fuzzy logic controller**

| V | D-V | N | Z | P |
|---|---|---|---|---|
| NB | D-duty | PB | PB | P |
| NS | | PB | P | P |
| Z | | P | Z | N |
| PS | | N | N | NB |
| PB | | N | NB | NB |

The rules base of fuzzy logic controller are shown in table 2.

## Result and discussion

As shown in Fig. 12, operation test of photovoltaic pumping system is carried out in two different sunlight levels 0 and 700 W/m$^2$, to take into account the sudden appearance of clouds during the day.

Table 3 illustrates the parameter's values of the PV pumping system elements.

Fig. 13 shows the variation of the state of charge of super capacitor. Indeed, its discharge is carried out in real time with the appearance of the clouds, which validates the robustness of the fuzzy logic controller and its decision-making speed.

The state of charge of super capacitor reaches 80 % for 400 seconds, it is the result of the fast charging of this storage device. the duration of its discharge is longer, therefore it benefits from a sufficiently wide output for the DC pump power supply.

The start of DC pumping motor requires a stronger current, which is why the duty cycle, shown in Fig. 14, increases up to 80 %, so that the speed, shown in Fig. 15, reaches its nominal value. Then the duty cycle decreases to 60 % because the speed keeps its stability around its nominal value.

The relation between the duty cycle and the pumping motor speed is explained in Fig. 16 (see the 2nd side of the cover) which illustrates a surface representation of base rule of fuzzy logic controller. Indeed the duty cycle increases when the difference between the measured speed and the reference is negative, and consequently decreases in the opposite case.

Hence it is clear that the fuzzy logic controller is able to follow all the conditions of PV pumping system to ensure an even more stable pumping rate.

Table 3

**Values of Parameters of PV Pumping System**

| | |
|---|---|
| **PV panel** | |
| Ppv | 110 W |
| Impp | 3.15 A |
| Vmpp | 35 V |
| Icc | 3.45 A |
| Voc | 43.5 V |
| **Super Capacitor** | |
| Capacitance | 25F |
| Equivalent Series Resistance | 0.069Ω |
| **DC motor** | |
| Output Power | 200 W |
| Nominal Speed | 2350 RPM |
| Nominal Voltage | 40 V |
| Nominal Current | 5 A |
| **DC-DC Buck Boost Converter** | |
| Inductance | 0.432 H |
| Capacitance | 7.7 mF |

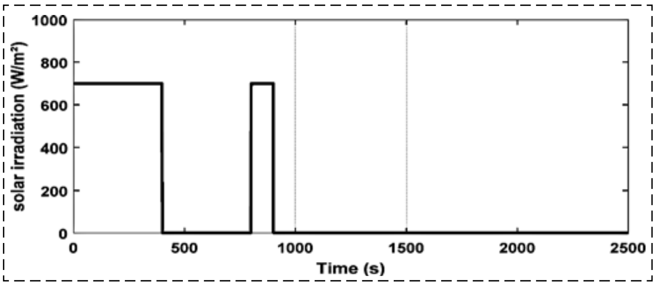

Fig. 12. Solar irradiation level

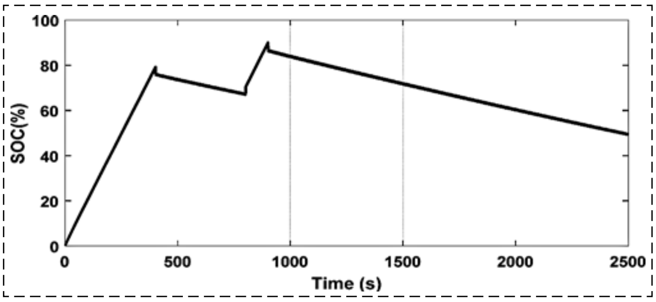

Fig. 13. State of charge of super capacitor

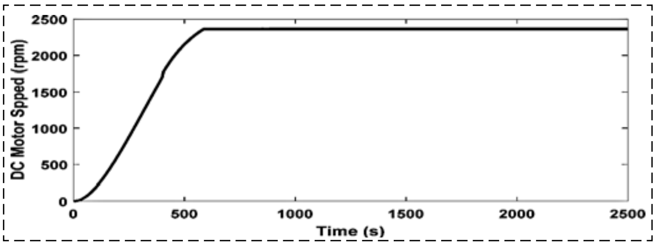

Fig. 14. Duty cycle of DC buck boost converter

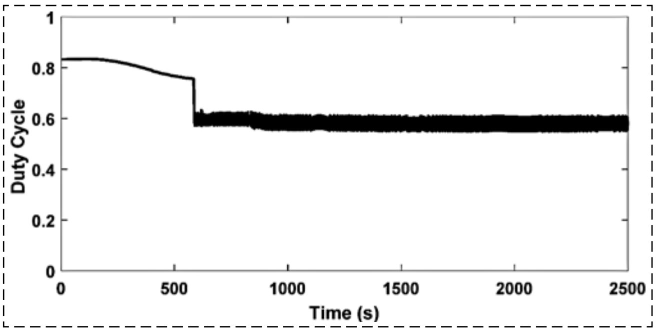

Fig. 15. DC motor Speed

## Conclusion

A study of energy storage performance and engine speed control is carried out in this paper to maintain the speed of the DC motor close at its nominal value despite the sunshine disturbances. The super capacitor installation has proven its rapid storage of large amounts of energy in short periods of sunshine and its ability to meet the need for a pumping motor to run at its nominal speed.

The stability of the pump motor speed is obtained following the implementation of a fuzzy logic controller which has a reflux, without the need for a mathematical model, as well as conditioning speed of the input and a better precision of decision-making.

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