JST: Smart Systems and Devices
*Volume 35, Issue 1, January 2025, 030-039*

# Control of Stand-Alone Hybrid Wind-Photovoltaic Energy System Using Fuzzy Logic

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**Abstract**

*Standalone hybrid wind-photovoltaic system performance is strongly dependent on the DC bus voltage and the ability to reach the point of maximum power under the variation of weather condition and load consumption. In the paper, the proportional-integral controller and bidirectional DC/DC converter are used to keep DC bus voltage in constant value. To obtain the maximum power from wind turbine and solar panel, a proposed method to find the point of maximum power combining fuzzy logic and perturb and observe method is introduced, in which a maximum power point tracking fuzzy logic controller with only one input is designed to obtain the maximum power from solar panel. The advantages of the MPPT fuzzy logic controller with one input are its simple structure, reducing the complexity in the steps of fuzzification, building fuzzy rules, and defuzzification compared to the maximum power point tracking fuzzy logic with two inputs. In order to avoid the over-charge and over-discharge of lithium-ion battery, a fuzzy logic supervisor is used. The simulation results in Matlab/Simulink software are presented to show the good performances of the proposed controllers in the standalone hybrid wind-photovoltaic system.*

Keywords: Wind energy, photovoltaic, hybrid system, maximum power point tracking, stand-alone system, battery, fuzzy logic control.

## 1. Introduction

In recent years, hybrid renewable energy systems have attracted a lot of research from scientists because of the economic and environmental benefits that they bring about. The hybrid system which consists of wind and photovoltaic (PV) has become popular, due to its high reliability and suitable for installation in different weather conditions.

The amount of power generation in hybrid wind-PV system is often stable because these two renewable energy sources can supplement each other. During the day, solar power is high, while wind power is lower. At night, solar power is almost zero, but the wind power is high due to high wind speed. In the summer, when solar energy is abundant, wind energy is less sufficient, and in the winter, solar energy decreases significantly, while the wind energy increases sharply.

The feature of complementing each's other energy between night and day, and between winter and summer is a very important feature that helps wind-solar system become a topic studied by many researchers [1-3].

In the remote areas where there isn't power grid, a stand alone hybrid wind-PV system is one of the effective solutions to supply electricity. The stand alone hybrid wind-PV system isn't connected to power grid, and the wind power and PV power often change under variation of weather condition. So, control of stand-alone wind-PV system always meets many challenges. The first challenge is the fluctuations in the DC bus voltage [4, 5]. The second challenge is to satisfy the load demand under the varation of power generation. The third chanllenge is to obtain maximum power from wind and PV [6-10].

In the literature, many studies showed that the stand-alone hybrid wind-PV system is nonlinear system. Using fuzzy logic controller in hybride renewable energy showed a lot of advantages comprared to traditional controllers. With the use of fuzzy logic, we no longer need an accurate model of the system (PV, wind turbine, inverter, boost converter) [11-14].

In [15, 16], the articles designed a fuzzy controller to manage energy in a wind-solar hybrid power system, however these articles did not design maximum power point tracking (MPPT) controllers to obtain maximum power from wind turbines and solar panel.

Authors in [17] presented a MPPT method for PV pannel. This method combine fuzzy logic and traditional method incremental conductance (INC).

ISSN 2734-9373
https://doi.org/10.51316/jst.179.ssad.2025.35.1.4
Received: Jul 11, 2024; revised: Aug 30, 2024;
accepted: Sep 26, 2024

Authors in [18] designed a fuzzy controller for energy management in an independent wind hybrid power system. In [19], the article designed a fuzzy logic MPPT controller to obtain the maximum power from the wind turbine.

The simulation and control of hybrid wind-PV system is shown in [20]. However, the article didn't integrated the MPPT controller for wind turbines.

In this paper, a stand-alone hybrid system including a varibale speed wind turbine, a PV panel and a lithium-ion battery bank is proposed. The wind turbines is directly connected to a permanent magnet synchronous generator, this has many advantages such as increased reliability, reduced maintenance costs, and reduced mechanical stress on the generator. To obtain the maximum power from wind turbines and PV panel, and reduce fluctuations around the point of maximum power (PMP), two fuzzy logic MPPT controllers will be designed. The fuzzy logic MPPT controller for PV panel has a simple structure with only one input, so the steps of fuzzification, defuzzification, and building fuzzy composition become easier. In order to keep the DC bus voltage constant, a proportional-integral (PI) controller and a DC/DC bidirectional converter are used. To avoid the overcharge and overdischarge of lithium-ion battery, a fuzzy supervisor is designed.

Most of fuzzy logic MPPT controllers for PV panel in the literature have two inputs [17; 21-23]. This causes complexity in steps of fuzzification, defuzzification, and building fuzzy composition.This paper will design one input fuzzy logic MPPT controller which have simple structure and high performance.

Most of articles in the literature only focus on the design of fuzzy logic MPPT controller or fuzzy logic supervisor or PI controller in hybride wind-PV system, but have not integrated all four controllers in the same system. The main contribution of the paper is the integration of three fuzzy logic controllers and one PI controller in a hybrid wind-PV system to optimize the system performance.

## 2. System Description

The proposed system consists of a a 20x10 PV arrays (15.12 V, 0.902 A at 1000 W/m², 25 °C), a wind turbine driven permanent magnet synchronous generator (PMSG) (12 kW, 67 Nm, 1700 rpm) and a lithium-ion battery (600 V, 10 Ah) to power three AC loads (3 kW, 3 kW and 2 kW) (Fig. 1).

In order to obtain the maximum power of PV panel and wind turbine, the MPPT fuzzy logic controller 1 adjusts the duty cycle $D_1$, and the MPPT fuzzy logic controller 2 adjusts the duty cycle $D_2$ .

If the hybrid power is lower than the load power and the battery capacity is sufficient, the PI controller will control the battery to work at discharge state. The battery will start to provide the necessary power.

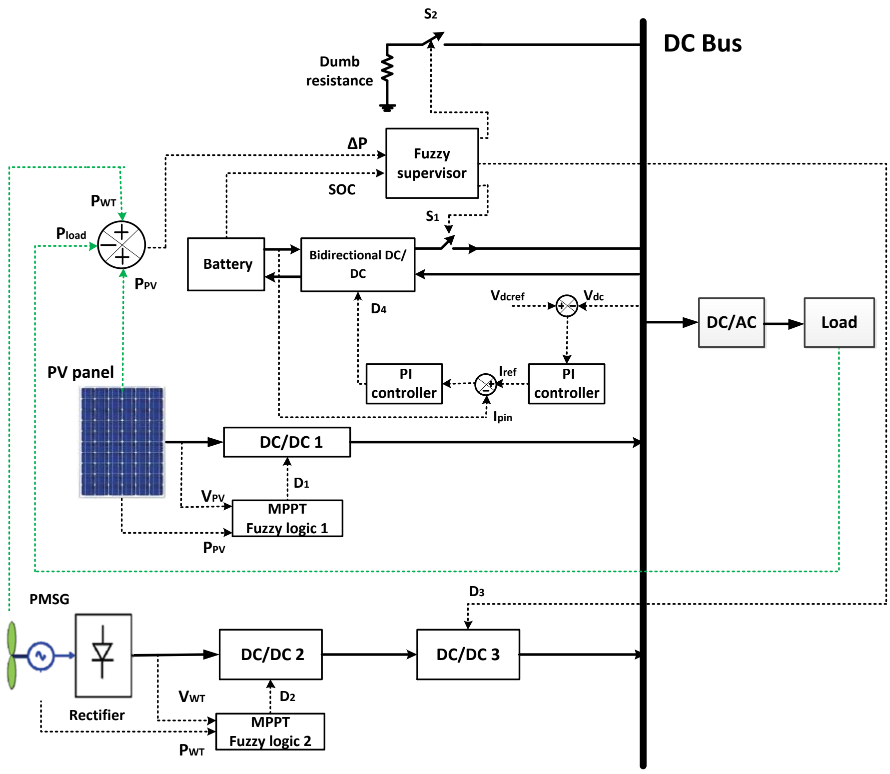


Fig. 1. The proposed hybrid wind-PV system

If the hybrid power is higher than the load power and the battery capacity is not full, the PI controller will control the battery to work at charge state. The surplus power will be stored in the battery.

When the wind speed changes, the output voltage of boost converter DC/DC 2 varies a lot. A boost converter DC/DC 3 is used to stabilize the DC bus voltage. We adjust the duty cycle $D_3$ to keep the output voltage of the boost converter DC/DC 3 in constant value.

The fuzzy supervisor have two inputs and three outputs. Two inputs are the battery state of charge (*SOC*) and the difference between hybride wind-PV power and load power ($\Delta P$). Three outputs are the duty cycle $D_3$ , the switch $S_1$ and the switch $S_2$ .

If the hybrid power is lower than the load power and the battery capacity is insufficient, the fuzzy supervisor will open the switch $S_1$ to avoid the over-discharge state of battery. If the hybrid power is higher than the load power and the battery capacity is full, the fuzzy supervisor will close the switch $S_2$ to avoid the over-charge state of battery. The exceed power will be dissipated into a resistor.

## 3. Bidirectional DC/DC Converter

A bidirectional DC/DC converter is used to perform the energy exchange between solar panel, wind turbine, AC loads, and battery.

The DC bus voltage $V_{dc}$ is controlled to always be stable at the $V_{dcref}$ through two closed control loops ( Fig. 2).

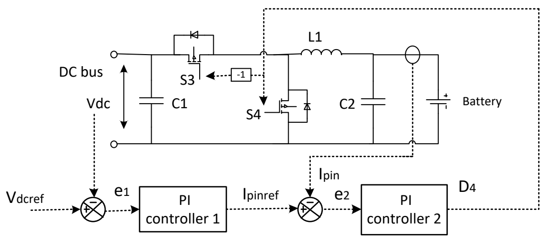


Fig. 2. Bidirectional DC/DC converter

In the first control loop, the measured value of $V_{dc}$ is compared to $V_{dcref}$ . The error $e_1$ is the input of PI controller 1. The output of PI controller 1 will be the set current value $I_{pinref}$ of battery. In the second control loop, the measured value of battery current is compared to $I_{pinref}$ . The error $e_2$ is the input of PI controller 2. The output of PI controller 2 will be duty cycle $D_4$ of bidirectional DC/DC converter.

When $V_{dc}$ is greater than $V_{dcref}$ , the measured value of battery current $I_{pin}$ is controlled to reach a negative value. Therefore, the battery is charged. The bidirectional DC/DC converter operate in buck mode. When $V_{dc}$ is smaller than $V_{dcref}$ , $I_{pin}$ is controlled to reach a positive value. Therefore, the battery is discharged. The bidirectional DC/DC converter operate in boost mode.

## 4. Design of Fuzzy Logic MPPT Controllers

Fig. 3 is the power characteristic of PV according to voltage, and Fig. 4 is the power characteristic of wind turbine according to rotor speed. According to these two characteristic curves, we can use the pertube and observe (PO) method to find the PMP of PV panel and wind turbine. By changing the two duty cycles $D_1$ and $D_2$, then observing the relative displacement between the working point and the PMP, we can control the operating point closer to the PMP. In P&O method, the perturbation step $\Delta D$ is constant and nonzero.

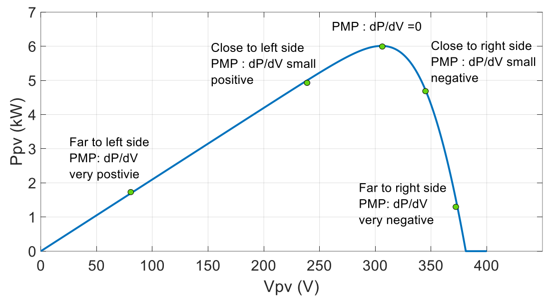


Fig. 3. PMP in function of PV voltage

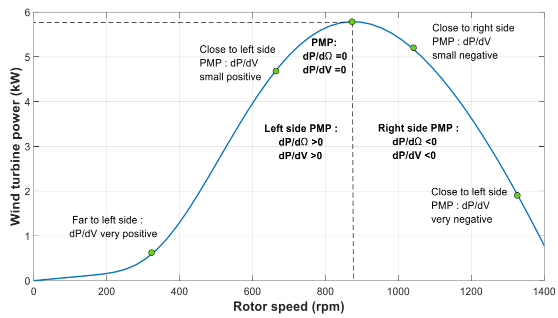


Fig. 4. PMP in function of rotor speed

If we choose a small value of $\Delta D$, the operating point is slowly shifted toward the PMP, and there is little fluctuation around the PMP. If we choose a large value of $\Delta D$, the operating point is quickly shifted toward the PMP, but there is a lot of fluctuation around the PMP.

When we use the PO method in hybrid wind-PV system, there are always fluctuations around PMP of PV panel and wind turbine, and this negatively affects the voltage quality in hybrid system.

In order to improve the disadvantages of PO method, the fuzzy logic MPPT controller is designed by the combination of PO method in fuzzy logic controller. The fuzzy logic MPPT controller will vary the pertuation step $\Delta D$ according to the distance between operating point and the PMP.

If the operating point is near the PMP, the fuzzy logic MPPT controller will choose a small value of $\Delta D$. If the operating point is far from PMP, the fuzzy logic MPPT controller will choose a large value of $\Delta D$, and if the operating point is PMP, the value of $\Delta D$ will be chosen to be zero. Thus, the operating point will quickly be controlled to PMP, and there are no more fluctuations around PMP. The advantages of fuzzy logic MPPT controller are the fast response time, reduction of fluctuations.

### *4.1. Fuzzy Logic MPPT Controller of PV System*

The fuzzy logic MPPT controller 1 has one input and one output. The input is the derivative of PV power with respect to PV voltage ($dP_{PV}/dV_{PV}$). The output is the difference between the current duty cycle and previous duty cycle $\Delta D_1$ of boost converter DC/DC 1.

When the operating point of PV panel is far to the left of PMP, the value of $dP_{PV}/dV_{PV}$ is very positive. The PV voltage should be increased quickly to reach PMP. When the operating point of PV panel is close to the left of PMP, the value of $dP_{PV}/dV_{PV}$ is positive but small. The PV voltage should be increased slowly to reach PMP. When the operating point of PV panel is the PMP, the value of $dP_{PV}/dV_{PV}$ is zero. The PV voltage should be kept in constant.

Choosing the number of fuzzy subsets depends on the designer's experience. If we choose a large number of fuzzy subsets, this will increase the computation time. If we choose a small number of fuzzy subsets, the control to achieve the PMP will take longer. In this controller, seven fuzzy subsets are used to convert from membership function values to linguistics variables. The selection of seven subsets is based on many experiments. Fig. 5 depicts the partitioning of fuzzy subsets and the shape of the membership function.

By using one input, constructing composition rules becomes simpler. In this case, there will be 7 fuzzy composition rules. The values of inputs and outputs are converted into variable languages to process in fuzzy logic controller as following:

- $dP_{PV}/dV_{PV}$[VeryNegative(VN),Negative(N), SmallNegative(SN),Zero(Z), SmallPositive(SP), Positive(P),Very Positive (VP) ].
- $\Delta D_1$ [-2%, -1%, 0.5%, 0%, +0.5%, +1%, +2% ].

The MPPT fuzzy controller use the min-max inference and Tagaki-Sugeno type and center of gravity method to operate. Examples are:

- If $dP_{PV}/dV_{PV}$ is Very Positive, then $\Delta D_1$ = -2%.
- If $dP_{PV}/dV_{PV}$ is Positive, then $\Delta D_1$ = -0.5%.
- If $dP_{PV}/dV_{PV}$ is zero, then $\Delta D_1$ = 0%.
- If $dP_{PV}/dV_{PV}$ is Very Negative, then $\Delta D_1$ = +2%.

Fuzzy rules are described in Table 1.

Table 1. Rules of $\Delta D_1$

| | $dP_{PV}/dV_{PV}$ | | | |
|---|---|---|---|---|
| | VN | N | SN | Z |
| $\Delta D_1$ | +2% | +1% | +0.5% | 0% |

| | $dP_{PV}/dV_{PV}$ | | |
|---|---|---|---|
| | SP | P | VP |
| $\Delta D_1$ | -0.5% | -1% | -2% |

The output of the converter DC/DC 1 are calculated by:

$$D_1(k) = D_1(k-1) + \Delta D_1(k)$$

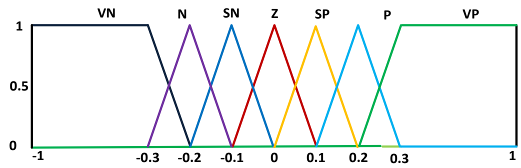


Fig. 5. Membership function of input $dP_{PV}/dV_{PV}$

### *4.2. Fuzzy Logic MPPT Controller of Wind Turbine System*

Authors in [10] showed that for each wind speed there is a value of the rotor speed that the wind power reaches the maximum power. The voltage $V_{WT}$ is proportional to rotor speed of PMSG. We can adjust duty cycle $D_2$ to change $V_{WT}$, thereby changing rotor speed of PMSG. The fuzzy logic MPPT controller 2 is based on this principle.

The fuzzy logic MPPT controller 2 has two inputs and one output. The first input is the derivative of wind turbine power with respect to output voltage of rectifier ($dP_{WT}/dV_{WT}$). The second input is the derivative of the first input ($dP_{WT}/dV_{WT}$)’. The output is the difference between the current duty cycle and previous duty cycle $\Delta D_2$ of boost converter DC/DC 2.

In this case the MPPT controller needs two inputs due to the complex physical characteristics and nonlinearity of the wind power system. In this case, up to 30 fuzzy composition rules must be used. In some cases, the value of $\Delta D_2$ is chosen to be zero, which significantly reduces the oscillation and increases the response time of the controller.

When the operating point of wind turbine is far to the left of PMP, the value of ($dP_{WT}/dV_{WT}$) is very positive, and if the value of ($dP_{WT}/dV_{WT}$)’ is positive, it means the operating point is moving away from PMP. At that time, duty cycle $D_2$ needs to decrease quickly to increase the voltage $V_{WT}$, thereby rapidly increasing the rotor speed to reach PMP.

When the operating point of wind turbine is close to the left of PMP, the value of ($dP_{WT}/dV_{WT}$) is positive but small, and if the value of ($dP_{WT}/dV_{WT}$)' is positive, it means the operating point is moving away from PMP. At that time, duty cycle $D_2$ needs to decrease slowly to increase the voltage $V_{WT}$, thereby slowly increasing the rotor speed to reach PMP.

When the operating point of wind turbine is to the left of PMP, the value of ($dP_{WT}/dV_{WT}$) is positive, and if the value of ($dP_{WT}/dV_{WT}$)' is negative, it means the operating point is approaching PMP. At that time, duty cycle $D_2$ needs to remain the same.

The values of inputs and outputs are converted into variable languages to process in fuzzy logic controller as follows:

- $dP_{WT}/dV_{WT}$ [Very Negative(VN), Negative(N), SmallNegative(SN),Zero(Z),Small Positive(SP), Positive(P), Very Positive (VP) ].
- ($dP_{WT}/dV_{WT}$)' [VeryNegative(VN), Negative(N), Zero(Z) , Positive(P), Very Positive (VP)].
- $\Delta D_2$[-3%,-2%,-1%,-0.5%, 0%,+0.5%,+1%,+2%, +3% ]

Membership function of two inputs $dP_{WT}/dV_{WT}$ and ($dP_{WT}/dV_{WT}$)'are described in Fig. 6 and Fig. 7.

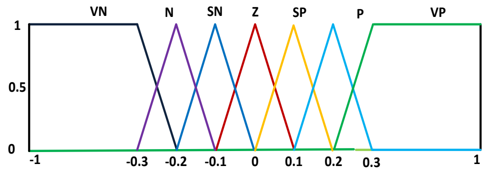


Fig. 6. Membership function of input ($dP_{WT}/dV_{WT}$)

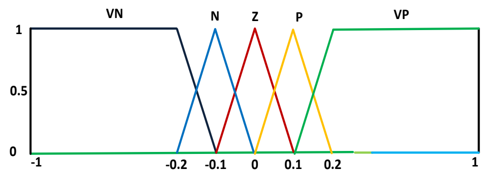


Fig. 7. Membership function of input ($dP_{WT}/dV_{WT}$)'

The MPPT fuzzy controller use the min-max inference and Tagaki-Sugeno type and center of gravity method to operate. The fuzzy rules are described in Table 2. Example is : If $dP_{WT}/dV_{WT}$ is very Positive and the ($dP_{WT}/dV_{WT}$)' is Positive, then $\Delta D_2$ = -3%.

The output of the converter DC/DC 2 is calcultaed by the formula : $D_2(k) = D_2(k-1) + \Delta D_2(k)$

Table 2. Rules of $\Delta D_2$

| $\Delta D_2$ | | ($dP_{WT}/dV_{WT}$)' | | | | |
|---|---|---|---|---|---|---|
| | | VN | N | Z | P | VP |
| $dP_{WT}/dV_{WT}$ | VN | +3% | +3% | +1% | 0% | 0% |
| | N | +2% | +1% | +1% | 0% | 0% |
| | SN | +1% | +0.5% | +0.5% | 0% | 0% |
| | Z | 0% | 0% | 0% | 0% | 0% |
| | SP | 0% | 0% | -0.5% | -0.5% | -1% |
| | P | 0% | 0% | -1% | -1% | -2% |
| | VP | 0% | 0% | -1% | -3% | -3% |

**5. Design of Fuzzy Logic Supervisor**

The fuzzy logic supervisor is designed to avoid the over-charge and over-discharge of lithium-ion battery. It have two inputs and three outputs. The first input is *SOC*, and the second input is difference power between hybrid power and load consumption. Three outputs are switch $S_1$, switch $S_2$ and duty cycle $D_3$.

The values of inputs and outputs are converted into variable languages to process in fuzzy logic controller:

- $\Delta P$ [Negative, Small Positive, Positive, Very Positive].
- *SOC* [Empty, Medium, Full] .
- $S_1$ [ Close, Open].
- $S_2$ [ Close, Open].
- $D_3$ [Very Small (VS), Small(S), Medium(M), Big(B), Very Big(VB)].

The fuzzy logic supervisor use the min-max inference and Mamdani type and center of gravity method to operate. The fuzzy rules are described in Table 3, Table 4 and Table 5. Membership function of inputs and outputs are described in Fig. 8, Fig. 9, Fig. 10 and Fig. 11.

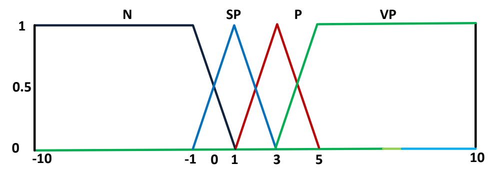


Fig. 8. Five terms of error power $\Delta P$

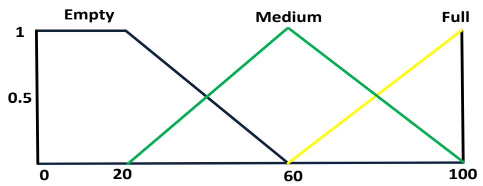


Fig. 9. Three terms of *SOC*

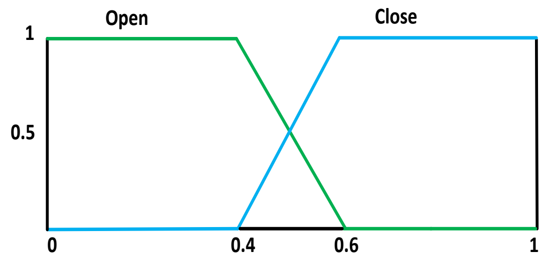


Fig. 10. Two terms of state $S_1$ and $S_2$

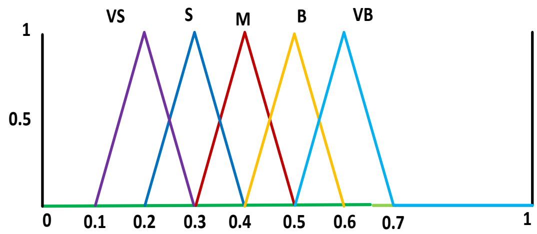


Fig. 11. Five terms of $D_3$

We have following examples of rules :

"If *ΔP* is Positive and *SOC* is Medium, then $S_1$ is closed and $S_2$ is opened and $D_3$ is small ".

"If *ΔP* is Negative and *SOC* is empty, then $S_1$ is opened and $S_2$ is opened and $D_3$ is very small ".

"If *ΔP* is Very Positive and *SOC* is Full, then $S_1$ is closed and $S_2$ is closed and $D_3$ is big ".

Table 3. Rules of $S_2$

| $S_2$ | | SOC | | |
|---|---|---|---|---|
| | | Empty | Medium | Full |
| ΔP | N | Open | Open | Open |
| | SP | Open | Open | Open |
| | P | Open | Open | Close |
| | VP | Open | Open | Close |

Table 4. Rules of $S_1$

| $S_1$ | | SOC | | |
|---|---|---|---|---|
| | | Empty | Medium | Full |
| ΔP | N | Open | Close | Close |
| | SP | Close | Close | Close |
| | P | Close | Close | Close |
| | VP | Close | Close | Close |

Table 5. Rules of $D_3$

| $D_3$ | | SOC | | |
|---|---|---|---|---|
| | | Empty | Medium | Full |
| ΔP | N | VS | S | M |
| | SP | S | B | VB |
| | P | M | B | VB |
| | VP | VB | B | B |

## 6. Simulation and Results

The models of proposed hybrid PV-wind system, MPPT fuzzy logic of PV panel, MPPT fuzzy logic of wind turbine, and fuzzy supervisor in Matlab/Simulink are described in Fig. 12 to Fig. 15.

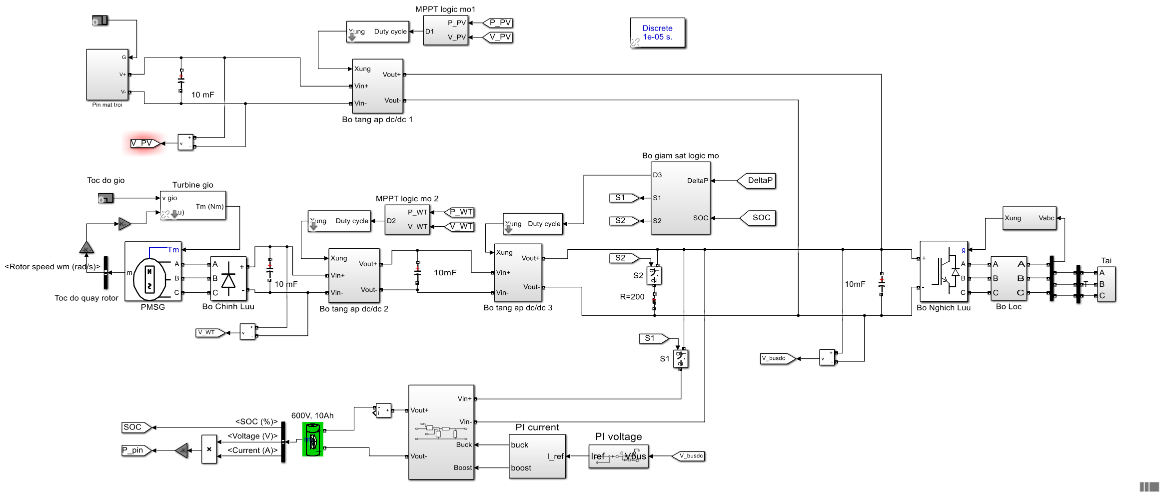

Fig. 12. The proposed hybrid wind-PV system

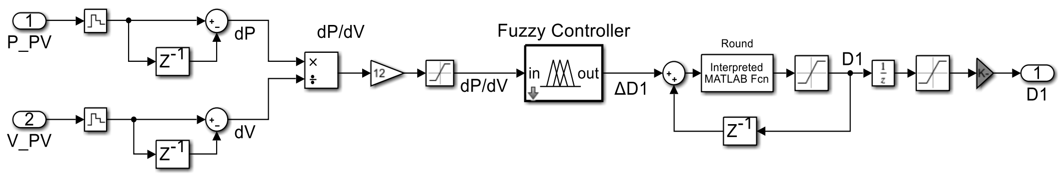


Fig. 13. MPPT fuzzy logic of PV panel in Matlab/Simulink

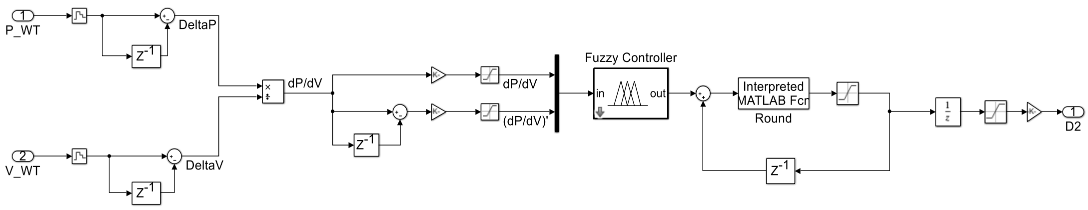


Fig. 14. MPPT fuzzy logic of wind turbine in Matlab/Simulink

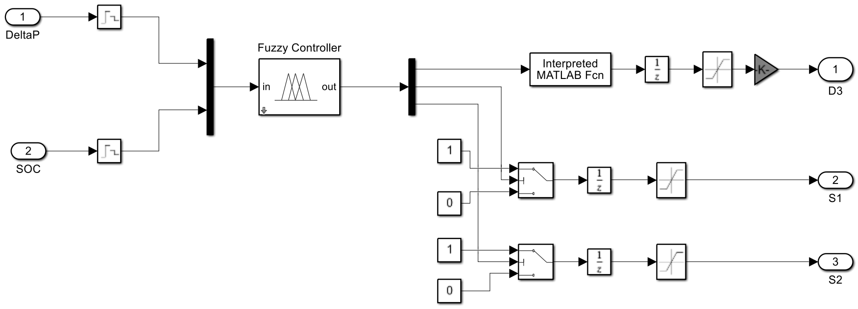


Fig. 15. Fuzzy supervisor in Matlab/Simulink

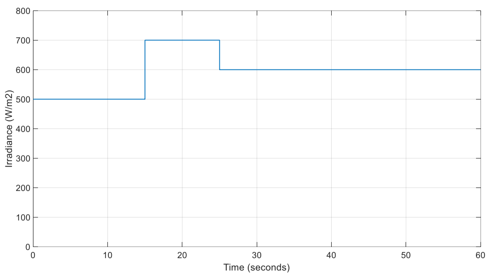


Fig. 16. Irradiance (W/m²)

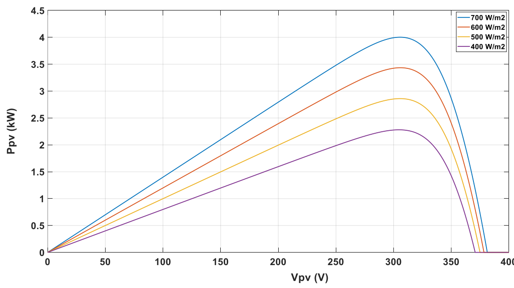


Fig. 18. *V-I* characteristics of PV panel at various irradiances

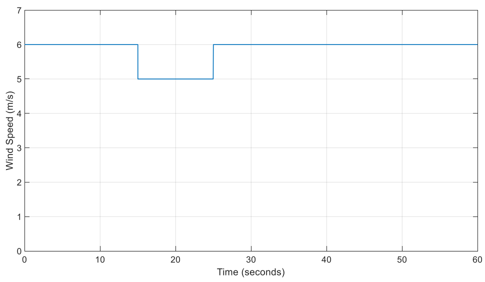


Fig. 17. Wind speed (m/s)

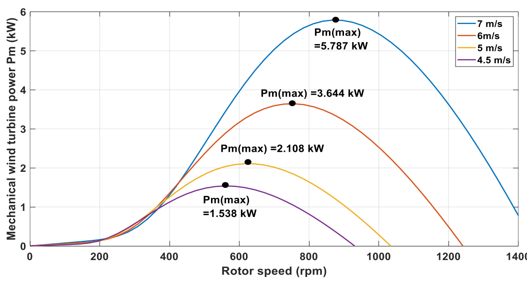


Fig. 19. Mechanical wind turbine power versus rotor speed at various wind speeds

Assume that at the initial time the state of charge of the battery *SOC* is 90% (full state). Load consumption, wind speed, and irradiance are changed within 60 seconds to verify the operation of the designed controllers (Fig. 16 and Fig. 17). The *V-I* characteristics of PV panel at various irradiances are showed in Fig. 18. The mechanical wind turbine power versus rotor speed at various wind speeds are showd in Fig. 19.

We can see that when the irradiance and the wind speed change at 15$^{th}$ and 25$^{th}$ seconds, and the load consumption changes at 50$^{th}$ seconds, the MPPT fuzzy logic controller 1 adjusts the duty cycle $D_1$ to get the maximum power from the solar panel, the MPPT fuzzy logic controller 2 controller adjusts the duty cycle $D_2$ to get the maximum power from the wind turbine (Fig. 20 and Fig. 21).

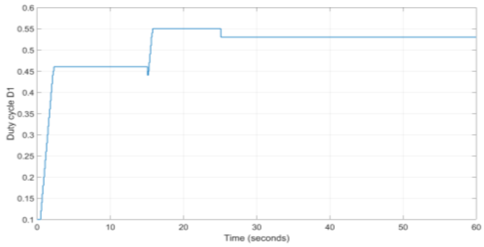


Fig. 20. Duty cycle $D_1$

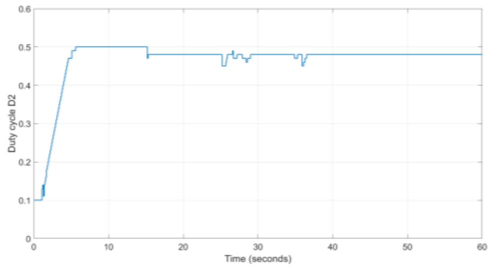


Fig. 21. Duty cycle $D_2$

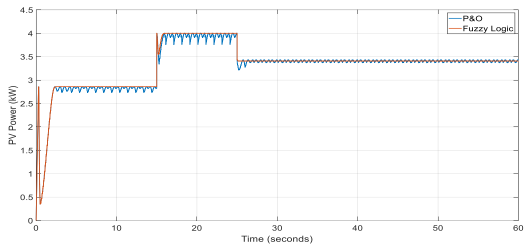


Fig. 22. PV power (kW)

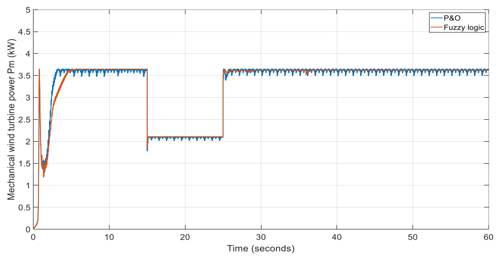


Fig. 23. Mechanical wind turbine power (kW)

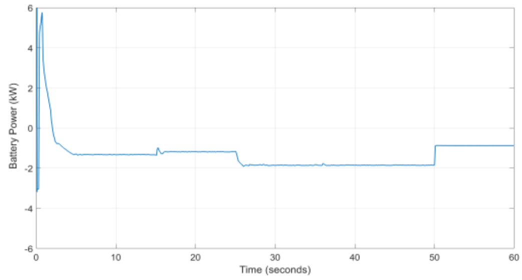


Fig. 24. Battery power (kW)

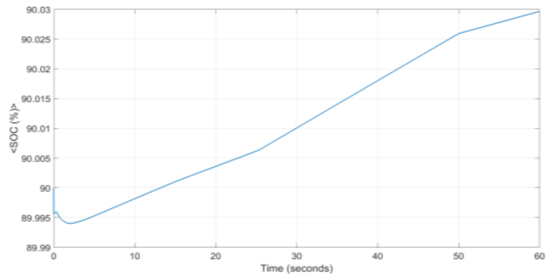


Fig. 25. Battery state-of-charge SOC (%)

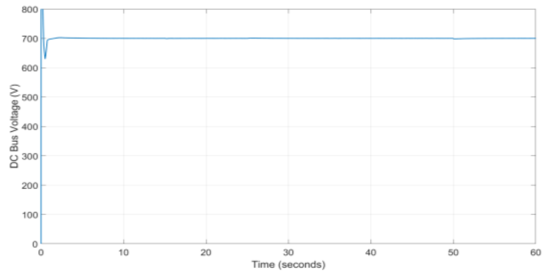


Fig. 26. DC bus voltage (V)

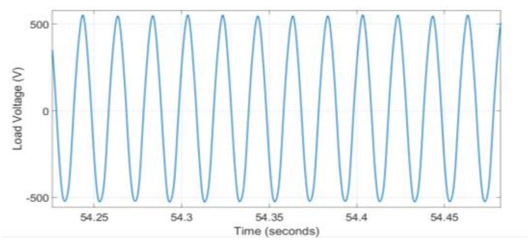


Fig. 27. Load voltage (V)

Once the maximum power point has been reached, the values of $D_1$ and $D_2$ remain the same. Therefore, there is no fluctuation around the PMP. This clearly improves the voltage quality in the system (Fig. 22 and Fig. 23).

To compare between PO MPPT method and fuzzy logic MPPT method, a simulation is performed with the same hybrid wind-PV system. The simulation results show that fuzzy logic MPPT controller work with better accuracy, and smaller oscillation at the maximum power point than PO one (Fig. 22 and Fig. 23).

At $10^{th}$ second, the load consumption is 4 kW. At $50^{th}$ second, the load consumption increases from 4 kW to 5 kW, and the hybrid power is greater than the load consumption. The PI controller controls the DC/DC bidirectional converter working in buck mode. At this time, the lithium-ion battery is working in charging mode to consume excess power in the system (Fig. 24 and Fig. 25).

When weather conditions and load consumption change, the PI controller always works well to keep the DC bus voltage stable at 700 V. Therefore, the voltage and frequency of the AC load are always at 380 V, 50Hz (Fig. 26 and Fig. 27).

## 7. Conclusion

In this paper, the MPPT fuzzy logic controller and PI controller and fuzzy logic supervisor were designed to manage energy for stand-alone hybrid wind-PV power system.

Simulation results have shown that with information about load consumption, *SOC* status of lithium-ion battery, power and voltage of solar panel and wind turbines, the controllers have worked well to meet the requirements of load demand when weather conditions change. The voltage of the DC bus is always kept at 700 V.

The power of PV panel and wind turbine are at its maximum value under the variation of loads and weather conditions.

As perspective, we will apply these controllers in experimental work to verify its efficiency and feasible.

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