FUZZY LOGIC-BASED ENERGY MANAGEMENT CONTROLLER FOR A HYBRID SOLAR WATER PUMPING SYSTEM

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Abstract- This paper presents the design, modeling, and analysis of a fuzzy logic-based energy management controller (EMC) for a hybrid solar photovoltaic (PV) water pumping system. The hybrid system is made up of solar modules, a variable speed diesel generator (VSDG), maximum power point tracking (MPPT) controllers, battery storage, an energy management controller, a bi-directional converter, and a direct current (DC) water pump. The EMC, based on fuzzy logic (FL), is responsible for managing the flow of energy throughout the hybrid system to ensure an undisturbed power supply to the water pump. The PV array, battery bank, and VSDG are all sized to power a 2.2 kW water pump and the maximum power point tracking controllers are proposed for improving the efficiency of PV modules. The system components are modeled in the MATLAB/Simulink environment. Several case scenarios were considered and simulated in the MATLAB/Simulink environment to evaluate the proposed system. The proposed EMC demonstrated the successful management and control of the energy flow within the hybrid system with less dependency on the VSDG. The EMC was also able to regulate the charging and discharging of the battery bank.

Keywords: energy management controller; fuzzy logic; maximum power point tracking controllers; variable speed diesel generator.

1. INTRODUCTION

With the fast growth of the renewable energy market, the idea of combining different power sources to form hybrid renewable energy systems (HRES) has received more attraction worldwide [1]. HRES can be defined as a combination of two or more renewable energy sources or a combination of renewable energy sources and conventional energy sources [2]. These systems offer an attractive configuration in remote areas for applications such as water pumping, electrification, lighting, and powering telecommunication systems. An important feature of HRES is that they combine different power technologies to get efficiencies higher than what could be attained using a single power source [3]. It has been demonstrated in the study [4] that HRES significantly reduces the total life cycle costs as compared to stand-alone power supplies and they provide a more reliable energy supply through the involvement of different energy sources. One of the common hybrid renewable energy systems is a PV/diesel hybrid system shown in **Fig.1**. A PV/diesel hybrid system combines the energy from PV modules with that from the diesel generator to power the load. The PV system may or may not include a battery bank, but the use of a battery bank is advisable to enhance power stability in the system. Another common example of HRES is a PV/wind hybrid system. A PV/wind hybrid system is mainly comprised of wind turbines, solar panels, controllers, batteries, and a backup generator for some instances.

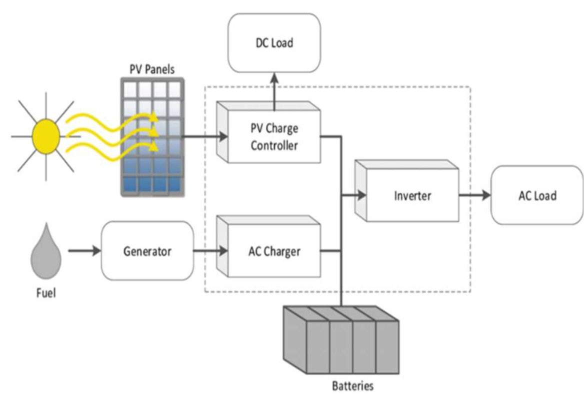

Fig. 1. PV/diesel hybrid system [5].

In reference [6], PV hybrid systems were proposed and studied for different applications like rural electrification and water pumping.
The main concern when dealing with hybrid renewable energy systems is the stochastic nature of wind and solar energy resources. The power output variation from these renewable energy sources leads to system instability and poor power quality which is not common in conventional power systems. Thus, the optimum design and sizing of the components of HRES are of prime importance for their economic and technical feasibility. Because of the complexity of the HRES, several optimization tools have been developed and applied in the design of these hybrid systems [7]. These optimization methods include classical, soft computing as well as hybrid techniques. Classical

optimization techniques find optimum solutions by differentiating the continuous objective function of a problem being solved. The examples of widely used classical techniques for optimizing HRES are the linear programming model (LPM), dynamic programming (DP), and the non-linear programming model (NLP). These classical optimization models have been incorporated in some HRES modeling packages such as the hybrid optimization model for electric renewables (HOMER), linear, interactive, and discrete optimizer (LINDO), and general algebraic modeling system (GAMS). In [8], a linear programming model in the GAMS software was proposed to find the optimum configuration of power supply from a mix of several renewable energy sources. The NLP and the DP have also been utilized for HRES optimization in the studies [9, 10] respectively. However, classical optimization techniques are limited in their ability to optimize HRES due to the systems' complexity, nonlinearity, multi-objective nature, dynamic and stochastic characteristics, and the need to integrate ancillary services [11]. These techniques struggle to handle the diverse range of renewable energy sources, their intermittent and variable nature, and the dynamic interactions between different components of the system. With the rise of computational intelligence (CI), several soft computing optimization techniques have emerged for solving complex, non-linear, and multi-objective trade-offs inherent in hybrid renewable energy system optimization [12]. These CI techniques include fuzzy logic (FL), artificial neural networks (ANN), genetic algorithms (GA), and particle swarm optimization (PSO). The literature reports voluminous research where CI techniques offer better results than classical methods in the design, sizing, control, and optimization of HRES. Fuzzy logic was utilized for the optimum power management of HRES in [13], ANNs were used in [14] for forecasting solar and wind energy for optimum sizing of HRES, and GAs were adopted for the design of an optimized hybrid renewable energy system in [15]. This paper explores the detailed design, modeling, and analysis of a fuzzy logic-based energy management controller for a hybrid PV water pumping system. Fuzzy logic stands out as the preferred choice for power management in HRES due to its adeptness in handling uncertainty inherent in sources like solar and wind power. By allowing for the representation of vague or imprecise information and employing linguistic variables and rules, fuzzy logic offers a flexible and adaptable control framework capable of real-time adjustments. Its rule-based approach facilitates the incorporation of domain knowledge, ensuring stable operation and enabling system operators to interpret control actions easily.

2. SOLAR WATER PUMPING

Solar photovoltaic water pumping (SPVWP) system is a technology that utilizes solar energy for water pumping [16]. It is similar to traditional water pumping systems, but the only difference is that the pumps are powered by solar energy instead of fossil fuel or grid electricity. From crop irrigation to domestic use, solar pumps meet a wide range of water needs. Also considering the unavailability of grid electricity in rural areas, SPVWP has become one of the promising technology in remote areas [17]. The design of solar water pumps is of prime importance for achieving a reliable and economical operation. Below are the benefits of using solar water pumping systems:

- *Extremely low operating cost* – a solar water pump uses solar energy at no cost at all. It does not depend on fuel or grid electricity so there are no recurring costs for electricity or fuel once the water pump is installed.
- *Low maintenance costs* – solar water pumps are easy to maintain compared to other pumps. They have relatively fewer moving parts and the chances for pump failure are fewer. Solar water pumps can run for years without any maintenance needed.
- *Eco-friendly* – common fuel-powered water pumps produce noise and air pollution whereas solar water pumps are environmentally friendly. They do not produce greenhouse gases that can cause global warming

Solar water pumps can be grouped into three categories according to their operations namely submersible, surface, and floating water pumps.

2.1 SOLAR WATER PUMPING SYSTEM CONFIGURATIONS

There are several types of configurations for solar water pumping systems. Every configuration has its advantages and disadvantages. Several factors should be considered when selecting the optimum configuration for a certain application. Listed below are some common setups for solar water pumping systems.

a) A direct connected solar water pumping system

The power from PV modules is directly connected to the pump for a directly connected solar water pumping system. The amount of water pumped is directly proportional to the solar irradiation hitting the PV panels. The advantages of this system are that it is simple and cheap compared to the battery-connected solar water pumping system. However, since there are no batteries, the pump only works during the day when there is enough solar insolation. A water storage tank is usually incorporated into this system to ensure the availability of water on cloudy days and at night. **Fig.2** shows a typical direct connected solar water pumping system.

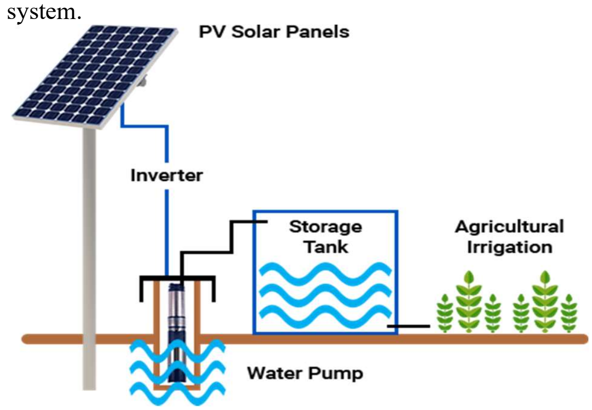

Fig. 2. Typical direct connected solar water pumping system

b) Battery-connected solar water pumping system.

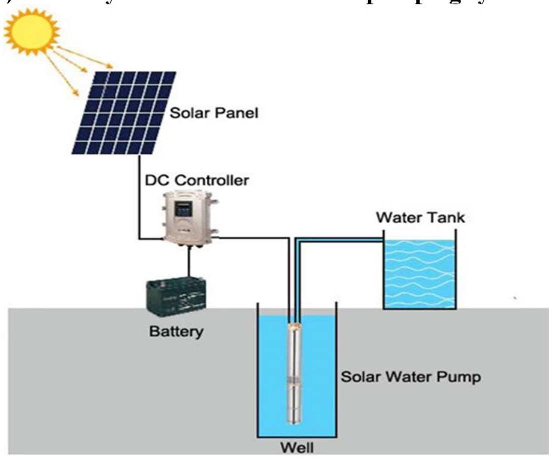

Fig. 3. Typical battery-connected solar water pumping system.

Battery-connected water pumping systems are made up of solar modules, charge controllers, batteries, and a water pump as shown in **Fig.3**. Depending on the application, the system may or may not include a water storage tank, and the water pump can also be powered by DC or AC. The batteries are charged using excess energy from the PV modules and they discharge to power the pump during the night or periods of low solar insolation.

c) Solar/wind hybrid water pumping system.

The solar/wind hybrid water pumping system is made up of a PV array and wind turbines to power the water pump. The system might include batteries or a water reservoir for energy storage. Since the peak operating hours for solar and wind occur at different times of day and year, this hybrid setup can power the water pump throughout the day even during the night. The only challenge is the unpredictable nature of these renewable energy resources and if there is no backup energy source, the hybrid system may fail to power the water pump.

d) PV/diesel hybrid water pumping system.

A solar/diesel hybrid water pumping system comprises a PV array, a diesel generator, and a water pump. The generator is switched on when the energy generated by the PV array does not meet the load demand. The battery bank or the water reservoir can be used as energy storage depending on the application. The main advantage of this setup is that the energy whether coming from the PV array or generator is always available to power the water pump. The diesel generator is always available to kick in. The challenge with this setup is that the two energy sources (PV array & constant-speed diesel generator) cannot power the water pump at the same time. If the power from the PV array is not enough, the PV array is disconnected, and the diesel generator is switched on to power the water pump. This means that the power generated by the PV array when the generator is on is not utilized in the hybrid system. However, recently, the concept of variable speed in diesel generators (DG) has been proposed for hybrid renewable energy systems applications [18]. The variable speed operation of DG allows an engine to be efficiently operated over its entire functional range. This allows the PV array and the generator to work together, complementing each other to power the water pump thereby achieving a higher solar energy penetration in the hybrid system. For this reason and others, this solar/diesel hybrid water pumping system setup offers a vast range of benefits as compared to other systems. **Fig.4** shows a typical solar/diesel hybrid system.

Fig. 4. Typical solar/diesel hybrid water pumping system.

3. SYSTEM DESIGN, SIZING AND MODELING

The solar/diesel hybrid water pumping system is made up of PV modules, MPPT charge controllers, a battery bank, a VSDG, a fuzzy logic-based energy management controller (EMC), a bi-directional converter, and the DC water pump as shown in **Fig.5**. The main aim of this hybrid system is to deliver uninterrupted power to the water pump at minimum diesel generator runtime and fuel consumption. The detailed design, sizing, and modeling of the system components are given in this section.

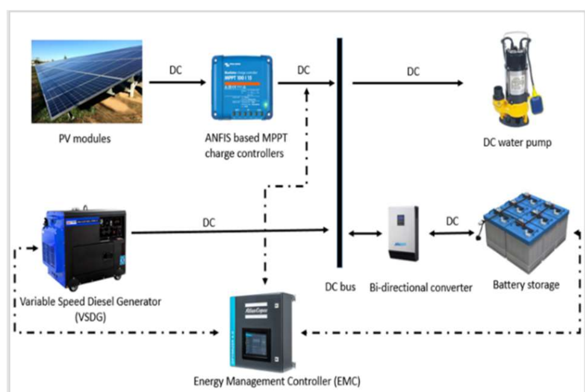

Fig. 5. The proposed solar/diesel hybrid water pumping system.

3.1 PV SYSTEM

Photovoltaic modules convert the energy coming from the sun into electricity using the photovoltaic effect. The PV modules are the main source of energy for the hybrid system. They are sized to power the water pump. The PV array is sized to power a 4SP3-18, 2.2 kW DC submersible water pump. **Table 1** gives the specifications for the water pump.

Table 1. Solar water pump specifications

Brand	4SP3-18
Max. pump head	185 m
Max. flowrate	100 L/min
Operating voltage range	60 V – 380 V
Max. current	12 A
Rated/optimum speed	3600 rpm
Speed range	1000 rpm – 4000 rpm

The PV array is sized using the peak sun hours (PSH) method given [19-24]. The sizing procedure is given below:

a) Calculating the total power consumption.
The total power consumption is given by calculating the total Watt-hours for all the appliances to be connected to the PV system. The water pump is estimated to be used between 10 am and 3 pm, which is 5 hours a day. **Table 2** gives the calculation of the total watt-hours per day.

Table 2. Total Watt-hours calculation

Appliance	Power rating	Working hours/day	Total watt-hours/day
Water pump	2200 W	5	11000

Then calculate the total watt-hours/day needed from the PV array, the system's energy losses should be considered. The losses are generally taken as 30% [21]. Thus, the total watt-hours needed from the PV array = 11000×1.3
$= 14300$ watt-hours/day

b) Sizing of the PV array
To get the size of the array, the total peak watt value must be determined. This is calculated using the PSH. A peak sun hour is a one-hour period during which the sun generates 1 kW of energy per square meter of the surface area per day. Assuming that this system is going to be used in South Africa, the average PSH value is 4.5.

Thus, the total watt-peak rating $= \frac{14300}{4.5}$
$= 3177.78\mathrm{W_p}$

To get the number of panels, the calculated total watt-peak rating is divided by the watt-peak rating of the selected modules. The PV module selected for this application is the 550W MBB half-cell module with the following specifications:

Table 3. PV module specifications

Electrical parameter	Rating
Rated maximum power (Pmax)	550 W
Open circuit voltage (Voc)	49.90 V
Maximum power voltage (Imp)	41.96 V
Short circuit current (Isc)	14.00 A
Maximum power current (Imp)	13.11 A
Module efficiency	21.3%

The number of solar modules $= \frac{3177.78}{550}$
$= 5.78$

Therefore, the total number of solar modules needed is **6** (rounding to the higher whole number). Since the DC water pump has a higher voltage operating range (60 V – 380 V), the solar panels are connected in series to produce a higher voltage.

3.2 VARIABLE SPEED DIESEL GENERATOR

The concept of variable-speed engines in diesel generators has emerged as a solution for low-load operation problems of constant-speed diesel generators [18]. The engine of a variable-speed diesel generator (VSDG) can select the optimum speed for a specific load. The proposed VSDG in this research work is comprised of a diesel engine and a double-fed induction generator (DFIG). The speed of the VSDG is controlled according to the state of charge (SOC) of the battery storage, the power from the PV modules, and the load demand. The configuration of the VSDG based on the DFIG is shown in **Fig. 6**.

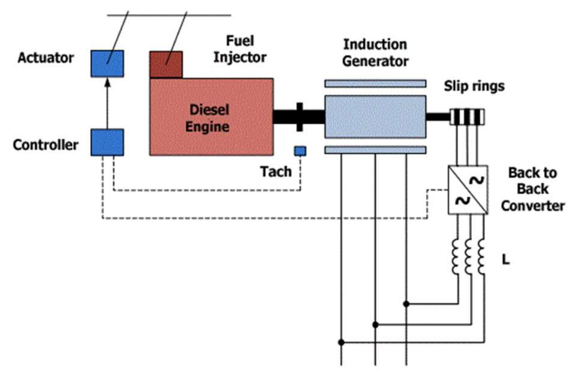

Fig. 6. DFIG based VSDG.

The VSDG specifications were calculated according to the rating of the water pump and **Table 4** gives the specifications of the selected VSDG. Advantages of this generator include extended engine life and lower fuel consumption compared to constant-speed diesel generators and the variable speed operation also reduces maintenance requirements.

Table 4. Piccolo – 3 kW Variable Speed Diesel Generator

Rated output power	3 kW
Engine RPM	Variable (2300-2900)
Starting system	Automatic starting
Generator type	Standby
Engine size	725 cc
Alternator type	Brushless

3.3 BATTERY STORAGE

To make the best use of the solar energy available and to reduce the use of the VSDG, batteries must be incorporated. Batteries enable the continuous power supply to the water pump in the event of power failure or under cloudy weather. The types of batteries used for solar energy systems include lead-acid, gel, lithium-ion, and nickel-based batteries. In this hybrid system, lithium-ion was used. The battery bank storage was sized using the procedure given in [19-21] and the specification of the battery is shown in **Table 5**.

Table 5. Pylontech US2000C 2.4 kWh 48 V Battery

Parameter	Rating
Nominal voltage	48 Vdc
Nominal capacity	50 Ah
Battery capacity	2400 Wh
DOD	95%

3.4 MAXIMUM POWER POINT TRACKING CONTROLLERS

To maximize the energy from PV modules, maximum power point tracking (MPPT) charge controllers are used. This research uses adaptive neuro-fuzzy inference system (ANFIS) based MPPT controllers for maximum power point tracking. The ANFIS method uses FL for transforming system inputs into desired outputs through interconnected neural networks. Each solar module has its own MPPT charge controller. The MPPT controllers are based on the fact that by knowing the maximum possible power output of a PV module for a given set of solar irradiance and temperature, the real-time MPP of the solar module can be perfectly tracked through the training of the ANFIS model.

3.5 ENERGY MANAGEMENT CONTROLLER

The energy management controller (EMC) is designed to satisfy the load demand regardless of the variation of the power coming from the renewable energy source. Thus, the EMC must select the appropriate energy source or a combination of energy sources at each instant to maintain a constant DC bus voltage to power the water pump. The EMC is based on fuzzy logic. Fuzzy logic control is an adaptive control that gives a robust performance for both linear and non-linear control systems. The following are the modes of operation of the energy management controller.

Mode 1: Total generated power from PV modules (P_{PV}) is equal to or greater than the load demand (P_L).
In this scenario, only the PV modules will be powering the pump. The controller must also check the state of charge (SOC) of the battery bank. If the SOC is less than the maximum state of charge of the battery (SOC_{max}), the controller must direct excess energy to charge the battery bank until it reaches SOC_{max}. When the battery bank reaches it SOC_{max}, the controller must terminate the charging to avoid overcharging the battery bank.

Mode 2: Total generated power from PV modules is less than the load demand.
The PV modules and the battery must power the pump in this mode. The controller also has to first check the SOC of the battery bank. If the SOC is greater than the minimum discharge limit, SOC_{min}, the controller must discharge the battery to meet the load demand until the battery bank reaches SOC_{min}.

Mode 3: Total power produced by the PV modules plus the battery storage is less than the load demand.
The VSDG must be started when the sum of power from the PV modules & battery bank does not meet the load demand. The VSDG must operate to constantly fill up the gap between the power produced by the PV modules & battery and the load demand. If the solar irradiance increases, the power from the PV modules also increases thereby charging the battery bank. When the battery bank charges and reaches the float level, SOC_{fl}, and if the sum of the power from the PV modules & battery bank meets the load demand, the VSDG is switched off.

The controller is designed using the IF-THEN rules which relate the inputs to the inputs to the outputs variables of the system. The fuzzy input variables are P_{PV} & SOC and output variables are the VSDG status ($VSDG_{status}$), VSDG speed ($VSDG_{rpm}$) and battery bank status (B_{status}). The controller is modeled and implemented in MATLAB/Simulink environment. The battery bank state of charge has 3 triangular membership functions which are described as LOW (0-20%), MEDIUM (20-80%), and HIGH (80-100%). The PV array's maximum power at STC is 3300 W (6 modules × 550Wp). Therefore, the membership functions of P_{PV} are described as LOW (0-1100 W), MEDIUM (1100-2200 W) and HIGH (2200-3300 W).

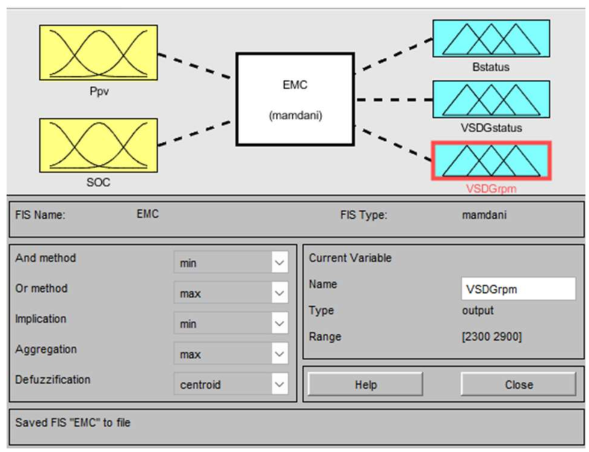

Fig. 7. Fuzzy logic designer for the EMC.

Table 6. Membership functions of the input variables

Input variables	LOW	MEDIUM	HIGH
SOC	0 - 20	20 - 80	80 - 100
P_{PV}	0 - 1100	1100 - 2200	2200 - 3300

For the output variables, the battery bank control has 3 membership functions namely, charging (0-0.2), discharging or charging (0.2-0.8), and discharging (0.8-1.0).

Table 7. Membership functions of the battery bank

Output variable	Charging	Discharging/ Charging	Discharging
B_{status}	0 – 0.2	0.2 – 0.8	0.8 – 1.0

The VSDG has an operating range of 2300 rpm to 2900 rpm. The VSDG generates a maximum power output of 3 kW at maximum speed. The membership functions of the VSDG control are designed in such a way that the speed of the generator has to be adjusted to generate the power that adds up to the PV array's output to meet the load demand when the power from the PV system is not enough to power the load as shown in **Table 8**.

Table 8. Membership functions of the VSDG speed

Output variable	LOW	MEDIUM	HIGH
$VSDG_{rpm}$	2300-2500	2500 - 2700	2700 - 2900

The last output variable of the EMC is the VSDG status which is described as OFF (0-0.5) and ON (0.5-1.0). The membership functions of this variable are designed to start the generator when the primary sources (PV array & battery bank) do not meet the load demand. The membership functions of VSDG status are shown in **Table 9**.

Table 9. Membership functions of the VSDG status

Output variable	OFF	ON
$VSDG_{status}$	0 – 0.5	0.5 - 1

Using the membership functions of different variables designed above, the IF-THEN rules of the FLC are created. **Table 10** shows nine different rules for different operational conditions of the hybrid system. In MATLAB/Simulink, the IF-THEN rules can be represented using the Rule Viewer. The Rule Viewer shows rules that are active or not active and it also indicates how each membership function influences the results of the system. **Fig. 11** shows the Rule Viewer of the designed EMC.

Table 10. Fuzzy rules for the EMC

1.	**IF** the P_{PV} is HIGH and SOC is HIGH **THEN** B_{status} is Discharging and $VSDG_{status}$ is OFF.
2.	**IF** the P_{PV} is HIGH and SOC is MEDIUM **THEN** B_{status} is Charging/Discharging and $VSDG_{satus}$ is OFF.
3.	**IF** the P_{PV} is HIGH and SOC is LOW **THEN** B_{status} is Charging and $VSDG_{status}$ is OFF.
4.	**IF** the P_{PV} is MEDIUM and SOC is HIGH **THEN** B_{status} is Discharging and $VSDG_{status}$ is OFF.
5.	**IF** the P_{PV} is MEDIUM and SOC is MEDIUM **THEN** B_{status} is Charging/Discharging, $VSDG_{status}$ is ON and $VSDG_{rpm}$ is LOW.
6.	**IF** the P_{PV} is MEDIUM and SOC is LOW **THEN** B_{status} is Charging, $VSDG_{status}$ is ON and $VSDG_{rpm}$ is MEDIUM.
7.	**IF** the P_{PV} is LOW and SOC is HIGH **THEN** B_{status} is Discharging and $VSDG_{status}$ is OFF.
8.	**IF** the P_{PV} is LOW and SOC is MEDIUM **THEN** B_{status} is Charging/Discharging, $VSDG_{status}$ is ON and $VSDG_{rpm}$ is MEDIUM.
9.	**IF** the P_{PV} is LOW and SOC is LOW **THEN** B_{status} is Charging, $VSDG_{status}$ is ON and $VSDG_{rpm}$ is HIGH.

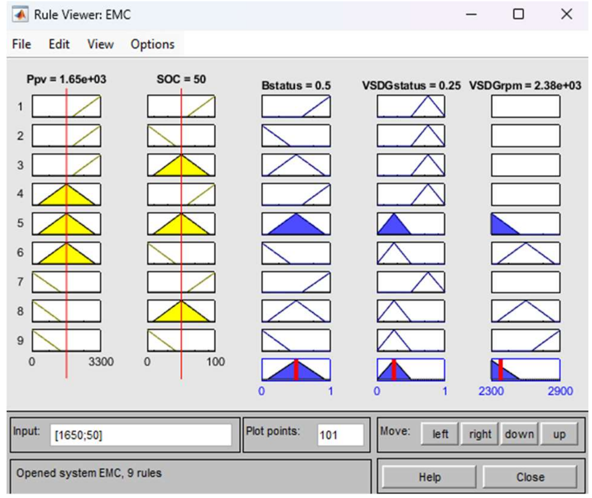

Fig. 8. Rule viewer of the FL-based EMC.

To show how each output depends on one or two of the inputs, the Surface Viewer is utilized. The Surface Viewer generates input/output surface mapping of the system as shown in **Fig.9, 10, and 11**.

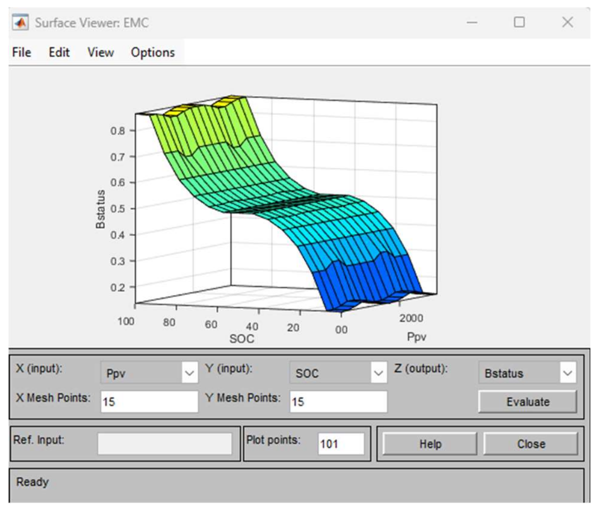

Fig. 9. A surface viewer of P_{PV} , SOC and B_{status}.

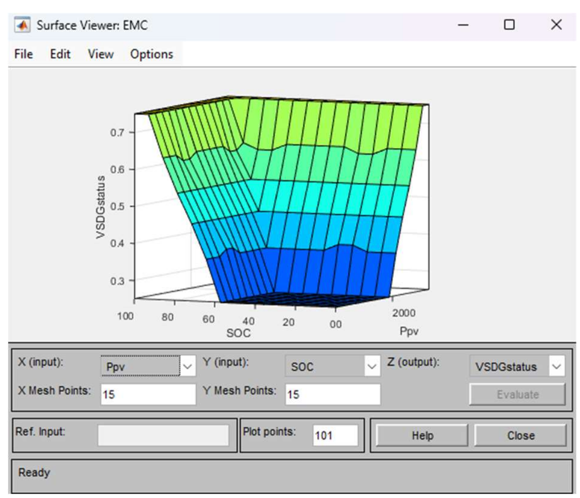

Fig.10. A surface viewer of P_{PV} , SOC and $VSDG_{status}$

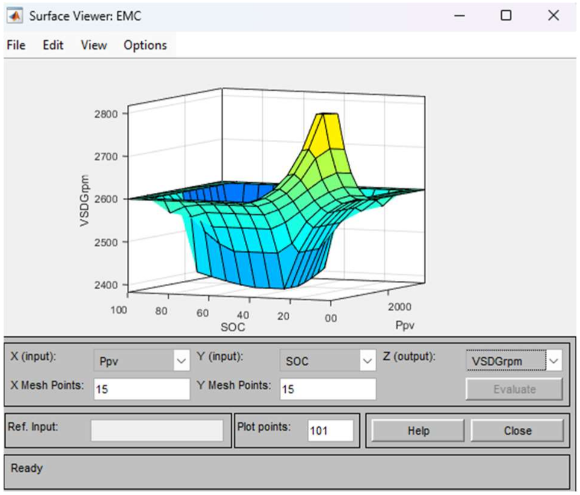

Fig. 11. A surface viewer of P_{PV} , SOC and $VSDG_{rpm}$.

3.6 BIDIRECTIONAL DC-DC CONVERTER

A bidirectional DC-DC converter is a type of power converter that allows energy to flow in both directions, from the input to the output and vice versa. These converters are integral to modern power electronics, offering flexibility and efficiency in managing power flow in various advanced applications. Their ability to operate in both directions makes them ideal for systems requiring energy storage and retrieval, contributing significantly to the efficiency and effectiveness of energy management systems. In this research, a buck-boost DC-DC converter is utilized to either step up (boost) or step down (buck) the voltage while allowing energy to flow in both directions between the battery storage and the DC bus. **Fig.12** shows the MATLAB model of the bidirectional converter implemented.

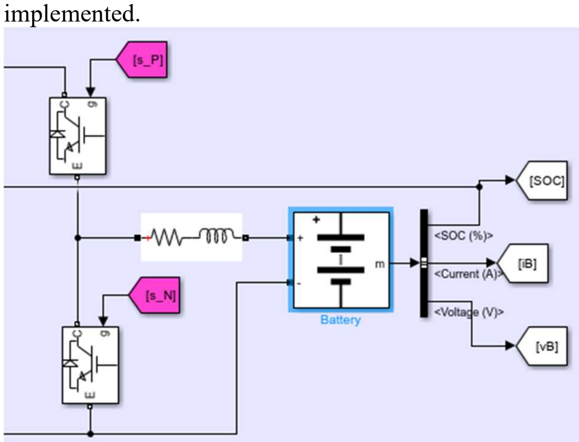

Fig. 12. MATLAB/Simulink model of the DC-DC bidirectional converter.

4. RESULTS AND DISCUSSION

As mentioned, the EMC must select the appropriate energy source or a combination of energy sources at each instant while maintaining a constant DC bus voltage at 240 V. Three case studies are simulated and studied to analyze the performance of the proposed system. In every case study, the P_{PV} is varied from HIGH (around 3300 W) (0 – 0.2) seconds, MEDIUM (around 2200 W) (0.2 – 0.4) seconds, and LOW (around 500 W) (0.4 – 0.6) seconds as shown in **Fig.13**. The P_{PV} is varied by changing the solar irradiance input to the PV array.

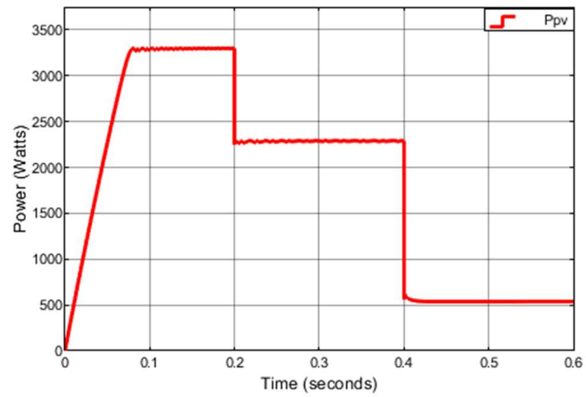

Fig. 13. P_{PV} variation from HIGH to LOW.

Case 1: The P_{PV} is varied from HIGH, MEDIUM, and LOW whilst the initial SOC is LOW.

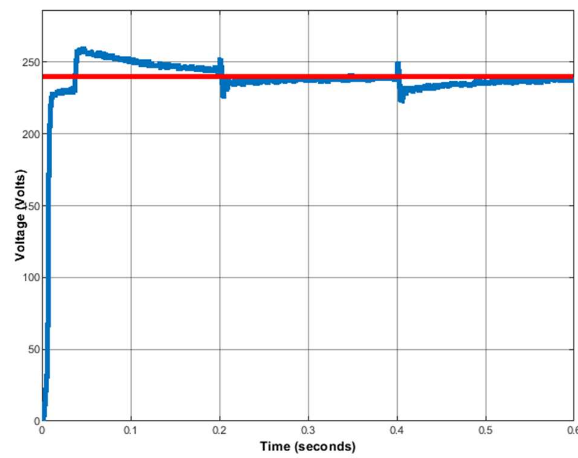

Fig. 14. DC bus voltage of case study 1.

In this case, the power from PV modules is varied from HIGH to LOW while the initial SOC is LOW. The simulation results are given below, including the DC bus voltage, VSDG speed, and water pump speed. **Fig.14** shows the results of the DC bus voltage.

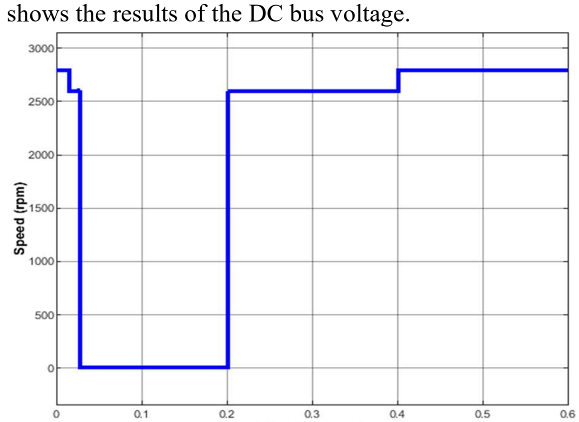

Fig .15. VSDG speed for case study 1.

The blue line represents the actual DC bus voltage of the system while the red line represents the target which is 240 V. It can be seen that the DC bus voltage rises from 0 V to just above 250 V. Since the power from PV modules is high between 0 to 0.2 seconds, the EMC selects solar modules as the only source of energy for this time frame, and excess energy is directed to charge the battery bank. The $VSDG_{rpm}$ is zero between 0 – 0.2 seconds as shown in **Fig.15** meaning that the generator is OFF.

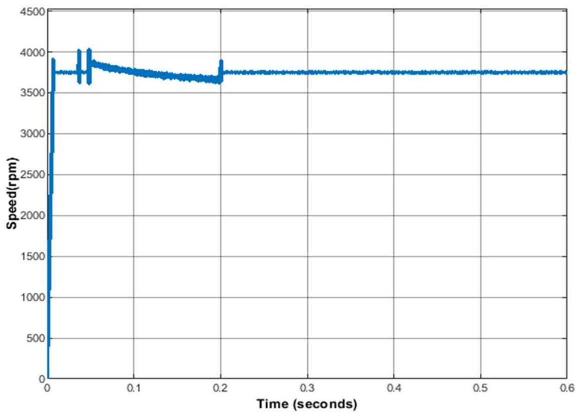

Fig. 16. Water pump speed for case 1.

Moreover, the EMC also makes sure that there is no further discharge of the batteries when the SOC is LOW. **Fig.16** shows simulation results for the speed of the water pump. The speed of the water pump rises to around 4000 rpm before it goes down to around its optimum speed of 3600 rpm. Kindly note that, since the P_{PV} starts at zero (between 0 to 0.2 seconds) and rises to the maximum as shown in **Fig.13**, the EMC controller read that small rising time as the P_{PV} is LOW and that's why the VSDG status shows a speed of between 2800 rpm to 2600 rpm before it goes to zero as shown in **Fig.15**. From 0.2 to 0.4 seconds, the P_{PV} is reduced to MEDIUM and the battery is still charging. At this point, the EMC activates the VSGD to operate at a medium speed of around 2600 rpm as shown in **Fig.15**. The water pump will be powered by the sum of the energy from the PV modules and VSDG to meet its power requirement. The EMC also makes sure that the DC bus voltage is kept around 240 V as shown in **Fig.14**. From 0.4 to 0.6 seconds, the P_{PV} is further reduced and the EMC makes the VSDG increase its operating speed to make up for the reduced power from the PV modules. The water pump will be powered by both the VSDG and PV modules. Because of the LOW P_{PV}, the speed of the VSDG is HIGH at 2800 rpm as shown in **Fig.15**. **Fig.16** shows the effectiveness of the EMC controller since it managed to maintain the speed of the water pump at around 3600 rpm.

Case 2: The P_{PV} is varied from HIGH, MEDIUM, and LOW whilst the initial SOC is MEDIUM.

In this case, the power from the PV modules is varied from HIGH to LOW whilst the initial SOC is MEDIUM. From 0 to 0.2 seconds, the EMC activates the charging/discharging of the battery bank, and the water pump will be powered by the PV modules and batteries. The VSDG status will be zero/off since the power from the battery and solar modules will be enough to power the water pump as shown in **Fig.18**. The EMC also regulates the DC bus voltage to operate at 240 V despite variations of P_{PV} as shown in **Fig.17**. From 0.2 to 0.4 seconds, the VSDG starts to run to add some power to the system since the power from the batteries and solar modules won't be enough to power the water pump. The VSDG operates at a lower speed of around 2400 rpm to make the hybrid system meet the power requirement of the water pump as shown in **Fig.18**.

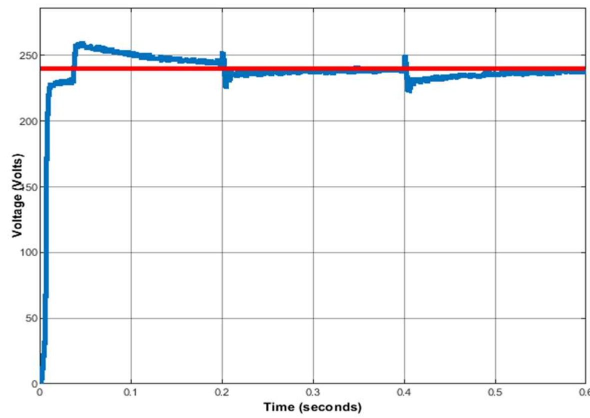

Fig. 17. DC bus voltage for case study 2.

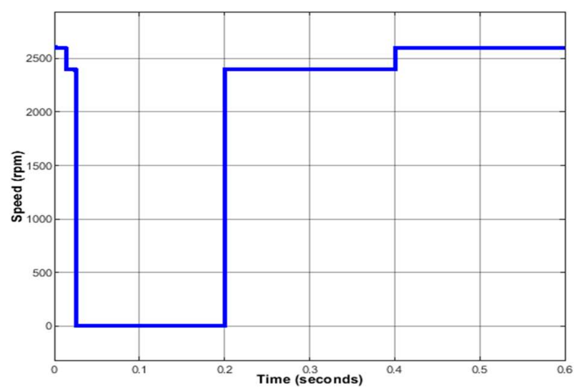

Fig. 18. VSDG speed for case study 2.

From 0.4 to 0.6 seconds, the P_{PV} is LOW. The EMC makes the VSDG increase its power output by increasing its speed from 2400 rpm to 2600 rpm as shown in **Fig.18**. The water pump will be powered by the VSDG, PV modules, and batteries. **Fig.19** shows the speed of the water pump.

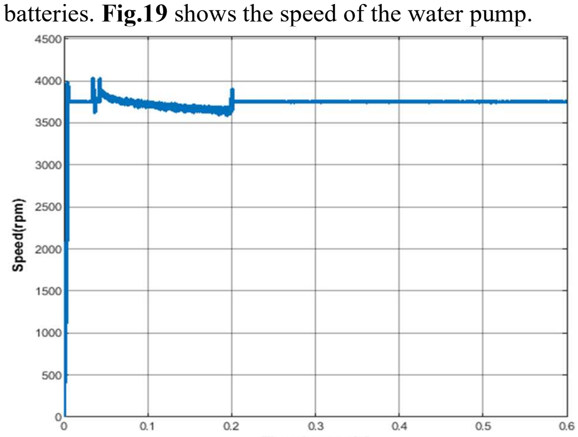

Fig. 19. Water pump speed for case study 2.

Case 3: The P_{PV} is varied from HIGH, MEDIUM, and LOW whilst the initial SOC is HIGH.

In this case, the power from PV modules is varied from HIGH to LOW whilst the initial SOC of the battery bank is HIGH. From 0 to 0.2 seconds, the P_{PV} is HIGH and the EMC selects PV modules and batteries as the power source of the hybrid system and the VSDG is off as shown in **Fig.21**.

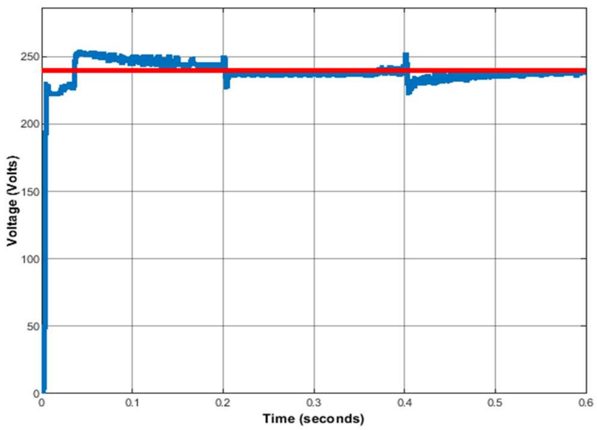

Fig. 20. DC bus voltage of case study 3.

From 0.2 to 0.4 seconds, the P_{PV} becomes MEDIUM and the power from PV modules and battery is still enough to power the water without the inclusion of the VSDG. The EMC can maintain constant DC bus voltage despite changes in P_{PV} as shown in **Fig.20**. The speed of the water pump for this timeframe is just above 3500 rpm because of the reduced power from the PV array.

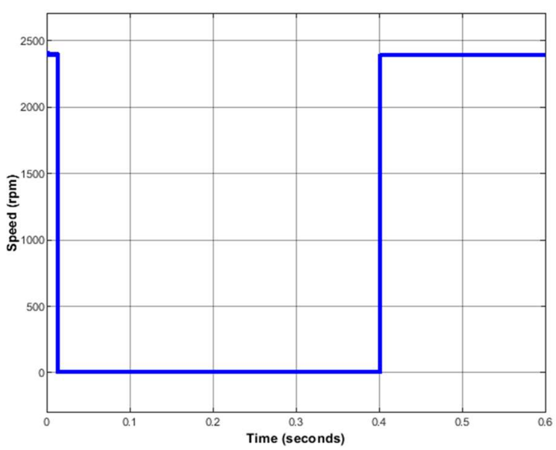

Fig .21. VSDG speed for a case study 3.

From 0.4 to 0.6 seconds, the P_{PV} becomes LOW. The EMC activates the VSDG to operate at a slower speed to make up for the reduced power from the PV modules as shown in **Fig.21**. The water pump will be powered with PV modules, a battery bank, and the VSDG. The speed of the water pump increases to around 3600 rpm when the VSDG is introduced as shown in **Fig.22**. It should also be noted that in all the case studies, the VSDG improves the system's power quality as shown in **Fig.22**, **Fig.19**, and **16**. The water pump becomes smoother whenever the generator is introduced into the system.

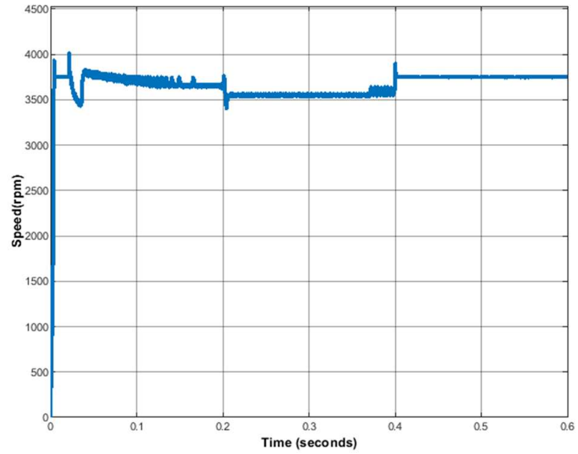

Fig. 22. Water pump speed for case study 3.

The presented work can be implemented in various practical applications. It can be utilized for agricultural, industrial, or basic water supply purposes both for rural and urban setups. For agricultural purposes, this hybrid water pumping system can be used for irrigation for medium to high-scale applications. It can also be used for industrial applications, such as underground dewatering at a mining site. For general water supply purposes, this system can be employed to supply water to a community, school, or hospital.

5. IMPLEMENTATION AND MAINTENANCE COSTS

This section discusses the implementation and maintenance costs of deploying this project and performing the cost-benefit analysis.

5.1 IMPLEMENTATION COSTS

Implementing a fuzzy logic-based energy management controller for a hybrid solar water pumping system involves several initial costs. The primary expenses include the purchase and installation of solar panels, MPPT charge controllers, a VSDG, a battery bank, the FL energy management controller, and the water pump itself. High-quality solar panels and batteries may require a significant upfront investment. Additionally, the development and integration of the fuzzy logic controller software into the system incur costs. These components must be carefully selected and sourced to ensure reliability and efficiency. The installation process includes site preparation, mounting of solar panels and electrical wiring, and setting up the water pump. Professional installation is often necessary to ensure optimal placement and connection of components, which can add to the overall cost. Additionally, setting up the fuzzy logic controller involves programming, testing, and calibration to adapt to local environmental conditions and water demand patterns. These tasks may require the services of skilled technicians and engineers, adding to the labor costs. Finally, obtaining the necessary permits and ensuring compliance with local regulations can also add to the implementation costs. This might involve environmental impact assessments, electrical safety inspections, and other regulatory requirements. Ensuring that the installation meets all legal and safety standards is crucial to avoid future fines or operational disruptions.

5.2 MAINTENANCE COSTS

Regular maintenance is essential to ensure the long-term performance and efficiency of the hybrid solar water pumping system. Routine tasks include cleaning the solar panels to remove dust and debris, inspecting and maintaining the water pump and associated plumbing, and checking the condition of electrical connections. Additionally, the fuzzy logic controller may require periodic software updates and recalibration to maintain optimal performance. Routine maintenance helps prevent minor issues from developing into major problems, ensuring the system's reliability. Over time, certain components of the system may need to be repaired or replaced. Batteries, for instance, typically have a lifespan of 5-10 years, after which their efficiency diminishes. The water pump and other mechanical parts may also wear out or suffer from damage, necessitating repairs or replacements. The costs associated with these replacements can vary based on the quality and specifications of the components. Continuous monitoring of the system's performance is crucial to address any issues that arise promptly. Investing in a monitoring system that provides real-time data on energy production, consumption, and system health can help in the early detection of potential problems.

5.3 COST-BENEFIT ANALYSIS

Conducting a cost-benefit analysis for a fuzzy logic-based energy management controller for a hybrid solar water pumping system involves assessing both the financial and non-financial benefits against the costs over the system's lifespan. Here's a detailed breakdown:

Table 11. Initial investment estimation

Cost Type	Estimated Price
Solar panels and installation	$1000
VSDG and installation	$800
Battery bank	$500
Water pump and installation	$700
MPPT charge controllers	$200
Bi-directional converter implementation	$100
FL energy management controller implementation	$300
Permits and regulatory compliance	$200
Total Initial Investment	**$3800**

Table 12. Operational cost estimation

Cost Type	Estimated Price
Routine maintenance (annually)	$600
Diesel fuel costs (annually)	$500
Total Annual Maintenance & Operational Costs	**$1100**

Table 13. Estimation of the benefits

Benefits Type	Estimated Price
Fuel consumption savings (annually), due to the use of solar PV modules	$1500
Increased agricultural yield (annually), due to a reliable water supply	$500
Reduction in carbon emissions (annually)	$200
Total Annual Benefits	**$2200**

To quantify the cost-benefit analysis, we use the net present value (NPV) calculations for ten years.

$$NPV = \sum \frac{net\ annual\ benefits}{(1+r)^t} - investment\ cost$$

Where r is the discount rate (5%) and t is the year.
Net annual benefits = total annual benefits – total annual costs.

$$NPV = \sum_{t=1}^{10} \frac{1100}{(1+0.05)^t} - 3800 = \mathbf{4694}$$

The positive NPV of $4694 over 10 years indicates that the project is financially viable. The benefits, including energy cost savings, increased agricultural productivity, and significant environmental and social impacts, outweigh the costs. This analysis supports the implementation of the fuzzy logic-based energy management controller for the hybrid solar water pumping system with a 2.2 kW DC water pump as a sound investment with substantial long-term benefits.

6. CONCLUSIONS

This research paper focuses on the use of AI techniques in solar energy technologies. The Fuzzy Logic (FL) concept is adopted for the energy management of a solar/diesel hybrid water pumping system. The Adaptive Neuro-Fuzzy Inference System (ANFIS) is also utilized for Maximum Power Point Tracking (MPPT) of solar modules. The hybrid water pumping system is comprised of PV modules, batteries, ANFIS-based MPPT charge controllers, FL-based EMC, VSDG, and a DC water pump. Solar modules are the main source of energy, and the batteries are utilized when the power from solar modules is not enough to power the load. The VSDG is activated when the power from the PV array and the battery bank is insufficient to power the water pump. The VSDG is proposed in this research work to achieve higher solar energy penetration in the hybrid system since the VSDG has a flexible operating range compared to constant speed generators. Simulation results proved that the EMC was able to manage the power distribution in the hybrid system, maintaining a constant DC bus voltage. The cost-benefit analysis was also performed, and the project proved to be financially viable. In conclusion, this research work was a great success, and it creates a knowledge base on ways to integrate a solar energy source with other energy sources.

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