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Fuzzy Logic Based Controller with Dedicated Safety Function for Hybrid Renewable Energy System

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Authors' contributions

This work was carried out in collaboration between both authors. Author NEC designed the study, performed the statistical analysis, wrote the protocol, wrote the first draft of the manuscript, and managed the literature searches. Author OOU managed the analyses of the study. Both authors read and approved the final manuscript.

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ABSTRACT

For the dual reasons of energy security and environmental and climate preservation, there has been a global campaign for drastic reduction in the use of fossil fuels and a consequential aggressive pursuit for the development of clean energy systems. Hybrid renewable energy systems, ahead of single source renewable energy systems, promise to be an effective alternative to the use of fossil fuels. However, if hybrid renewable energy systems must effectively and reliably serve as an alternative to fossil fuel use, then improvements in the control and management of energy flow among the renewable energy supplies, energy storage components, and the load is of very vital significance. More intelligent and optimized, and easy-to-develop control techniques need to be introduced to replace already existing conventional techniques. And very importantly, extra measures have to be taken to ensure longer battery life and the overall safety of the system. This work is a design of a fuzzy logic-based control system for managing energy flow in a hybrid renewable energy system. A dedicated output was incorporated in the fuzzy controller for controlling the load connection status. The results showed that the fuzzy logic controller accurately emulated expert decisions in monitoring the battery state-of-charge and renewable energy supply capacities, and effectively determining and controlling the battery charging and discharging functions. The

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employment of fuzzy logic control in the system eliminated the need for complex and tedious mathematical modelling as required in conventional control methods. Thus the system was easier to develop.

Keywords: Fuzzy logic control; renewable energy; hybrid renewable energy system; power management.

1. INTRODUCTION

Indeed, energy is fundamental to the fulfillment of basic individual and community needs such as lighting, transportation, provision of water, food, health and education. It follows, then, that energy is a major determinant of every country's economic and social development [1]. Fossil fuels, to this moment, remain the major source of energy, meeting three-quarters of total world energy needs [1]. Renewable energy, as an alternative to fossil fuels, has attracted global attention for the reason that it offers solution to all of the problems posed by the use of fossil energy sources. They are clean, safe, inexhaustible, and they satisfy the criteria for sustainability, videlicet, the ability to meet the energy needs of the present without compromising the ability of future generations to meet their own needs [2]. To assume any energy flow as "renewable" it should be replenished at least at the same rate as it is used [3]. Due to the weather-dependent nature of renewable energy sources, system reliability problems arise. If Renewable energy systems (RES) must prove to be the much desired alternatives to the use of fossil fuels, then it must be reliable. Research has shown that indeed some renewable energy sources complement each other. Therefore, reliability and efficiency can be achieved by combining more than one source of renewable energy in what is known as hybrid renewable energy systems (HRES). Hybrid systems capture the best features of each energy resource and can provide "grid-quality" electricity [4]. For the purpose of increased efficiency and reliability, HRES need to be monitored and controlled. The future prospects of renewable energy systems and its hybrid configurations are quite promising. Nonetheless, improper energy flow control, poor energy harvesting methods and/or incorrect battery charge/discharge algorithms result in not only low returns on investment, but also rapid system deterioration and possibly damage to the equipment [5]. Much work therefore has been done to improve on the reliability of renewable energy systems. In the area of extracting as much power as possible from the renewable energy sources, [6] designed a regulator to adjust the system speed of a wind turbine generator equipped with continuously variable transmission to operate at the highest efficiency point. [7] proposed a maximum wind power extraction system where a proportional controller is used to maintain the reactive power supplied by the wind turbine, and another proportional integral controller is used to maintain the wind turbine operation at an optimum tip speed ratio (TSR). [8] developed and implemented a MPPT algorithm on FPGA circuit for extracting maximum power from photovoltaic modules. Work has also been done to minimize the losses in renewable energy converters. [9] proposed a low cost multi-input dc-dc converter for integrating dc power in a transformer-less three-source hybrid renewable energy system. [10] discussed a three-phase voltage source inverter complex vector control scheme to be used in controlling the load side voltage in terms of the voltage amplitude and frequency. Research efforts have not left out the energy storage system efficiency for renewable energy systems. [11] explicitly quantified the dependence of optimal performance on storage and transmission capacity. [12] proposed the incorporation of a pumped hydro system and some lead-acid batteries to eliminate the low turn around efficiency of the electrolyzer and hydrogen generator system in a hybrid system in Ramea, Newfoundland, Canada. Meanwhile, [13] compared three power management strategies for the optimal performance of gel batteries in a hybrid renewable energy system. Optimized system sizing of renewable energy systems has also been a strong research focus. [14] developed a match evaluation method (MEM) based on renewable energy supply/demand match evaluation criteria to achieve low cost sizing of the system. Solar irradiation data and wind profile have been also employed for site-specific system sizing [15]. Very importantly, research work has intensified towards monitoring and control of power flow in renewable energy systems in order to take the best possible advantage of the complementary nature of the renewable energy sources to deliver constant and reliable power supply. [16–18] discussed various power management schemes for renewable energy systems. In recent times, suggestions have been made to integrate renewable energies into the smart grid to improve performance and realize cost effective power generation [19]. A number of research works have been done to increase viability and performance of various aspects of the smart grid. [20] discussed a novel dynamic clustering based energy efficient and quality-of-service (QoS)-aware routing protocol (called EQRP). While a data capacity-aware channel assignment (DCA) and fish bone routing (FBR) algorithm for wireless sensor network-based smart grid applications was proposed by [21]. Also, [22] presented honey bee mating optimization-based routing and cooperative channel assignment algorithms that address QoS requirements of most smart grid operations. However, the review on the role of smart grid in renewable energy [19] reports that the smart grid is not mature enough and needs more research on the same. Another advancement in renewable generation is the development of artificial intelligence (AI) techniques to address efficiency issues in renewable energy systems. A review of artificial intelligence techniques for sizing photovoltaic systems was done by [23]. The three AI techniques they reviewed are artificial neural networks, genetic algorithms and fuzzy logic. The highlighted advantages over traditional sizing methods include capacity to optimally size photovoltaic systems in situations where required data is incomplete. Adaptive neuro-fuzzy inference systems (ANFIS) have also been developed. ANFIS for variables selection and analysis of wind turbine wake effect, wind turbine power coefficient estimation, estimation of fractal representation of wind speed fluctuation, wind farm efficiency, and wind speed parameters sensitivity analysis has been presented [24–28]. In their work, [29] designed a HRES consisting of photovoltaic (PV), wind turbine generator (WTG), battery storage, and ethanol-blended gasoline system. They, however, limited the fuzzy logic controller to managing the charging and discharging of the battery. They took as inputs the difference between the total power generated and the load, and the battery state-of-charge. The output from the FLC was the battery charging current. This paper presents a controller developed for application in standalone HRES (consisting of Photovoltaic, wind turbine, and battery storage). Fuzzy logic was exploited for the power flow management among the energy sources, the load, and the battery. The Furthermore, an improvement over already existing FLC for HRES power management which is exhibited by this work was incorporating into the FLC the logic for disconnecting the load from all supplies in the event that there is insufficient power from the renewable energy sources and the battery voltage level is below the minimum required for discharge, or in situations of unforeseen accidents that may cause damages that could cripple the hybrid sources. This gave rise to adding a second output to the FLC. Thus, the efficiency afforded by the FLC was not limited to the logic that decides when to supply the load with the renewable energy sources or the battery power, or when to charge the battery, but was extended to the decision on when to turn off the load to avoid draining the battery below the depth-of-discharge, thus improving the battery life-span.

2. MATERIALS AND METHODS

2.1 Description of the Hybrid Renewable Energy System

The overall proposed hybrid renewable energy system consists of Photovoltaic (PV), Wind turbine generator (WTG), and battery storage. Distribution of power in the system is monitored using a fuzzy logic controller. The system block diagram is given below.

As shown in Fig. 1, all sources are connected to a main dc bus before being connected to the load through a main inverter. Each source is electrically connected with an appropriate power-electronic converter in order to get possibilities for power control actions. By attaching a converter to each power source and then connecting all sources to a central inverter, a control structure is developed which can be used for other combination of sources.

A DC/DC converter is interfaced to the PV source to produce a regulated DC power output. While an AC/DC converter is attached to the Wind Turbine generator, a bidirectional DC/DC converter is connected to the battery bank and then connected to the DC bus. An inverter is interfaced to the DC bus and connected to the AC load.

2.2 Control System

The control system was developed to successfully integrate all energy sources and the energy storage. The control unit was designed to exhibit the ability to prioritize the functionality of the power supplies. A fuzzy logic controller,

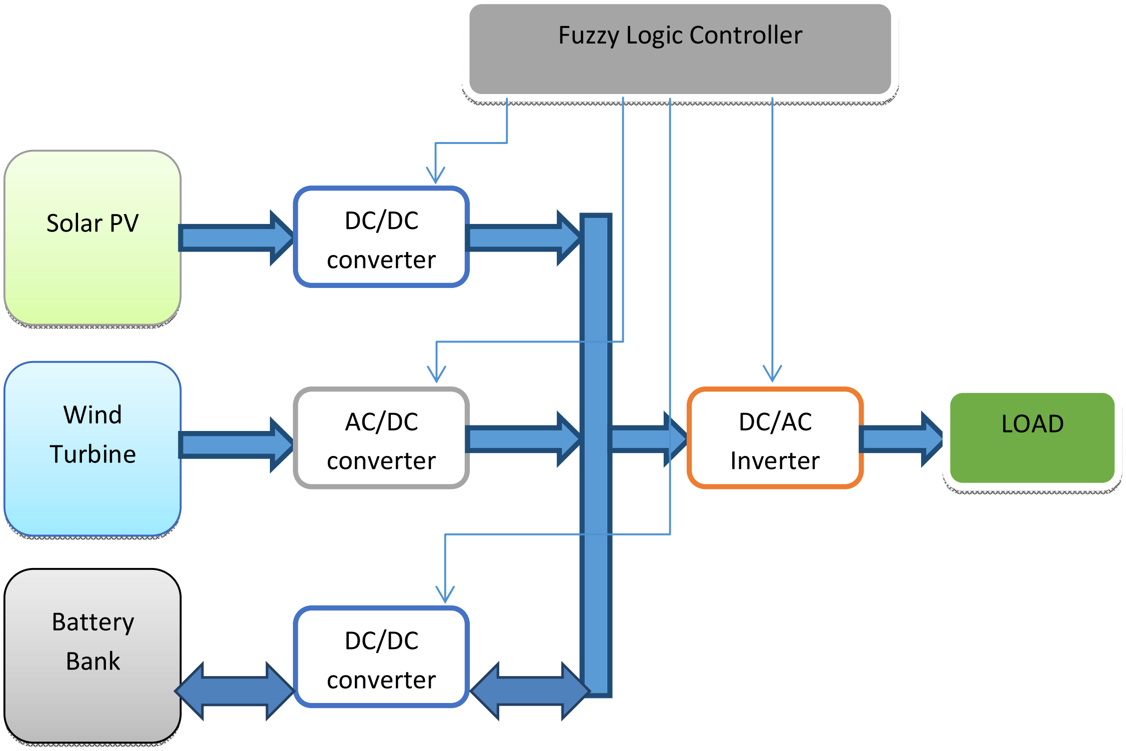


Fig. 1. Block diagram of the modeled hybrid system with fuzzy logic controller

which is the core of the control unit, was designed to manage the distribution of power in the hybrid system as well as manage the charging and discharging of the battery for performance optimization. The logic for cutting of the load from all supplies was integrated into the fuzzy logic controller. The use of fuzzy logic control introduced intelligence into the system. The power supplies are optimally selected by the intelligent power management system based on the availability of hybrid power supply, battery state-of-charge (SOC), and load demand. Power from the PV is designated as P_{PV}, whereas power from the wind turbine is given by P_{WT}. The load demand is given by P_L. The hybrid power P_H is given by

$$P_H = P_{PV} + P_{WT} \tag{2.1}$$

The flow chart for the flow of power is given in Fig. 2. When the combined power from the PV and wind turbine exceeds the load, the hybrid power supplies the load, and charges the battery in the trickle or normal charging mode depending on the SOC of the battery. While charging the battery in trickle mode, excess power is dumped to a heat sink. However, if the hybrid power is less than the load, the FLC checks for the SOC of the battery: if the SOC falls within the dischargeable range, the battery supplies the deficit in the load demand. But if the battery SOC is below the minimum specified for battery discharge, the FLC turns off the load and any power available from the hybrid, though less than the load demand, is used to charge the battery. Thus, the difference between the total generated power (PV and WTG) and load demand is obtained continually for proper management of the battery.

2.2.1 Fuzzy Logic Controller (FLC)

One of the basic advantages of fuzzy logic control over conventional techniques is that instead of delving into developing complex mathematical models for the system, you just need the knowledge of an expert on the behavior of such systems [30,31]. Therefore, appropriate consultations were made to obtain expert knowledge on the appropriate response the control output should have under given input conditions. These included looking up scholarly

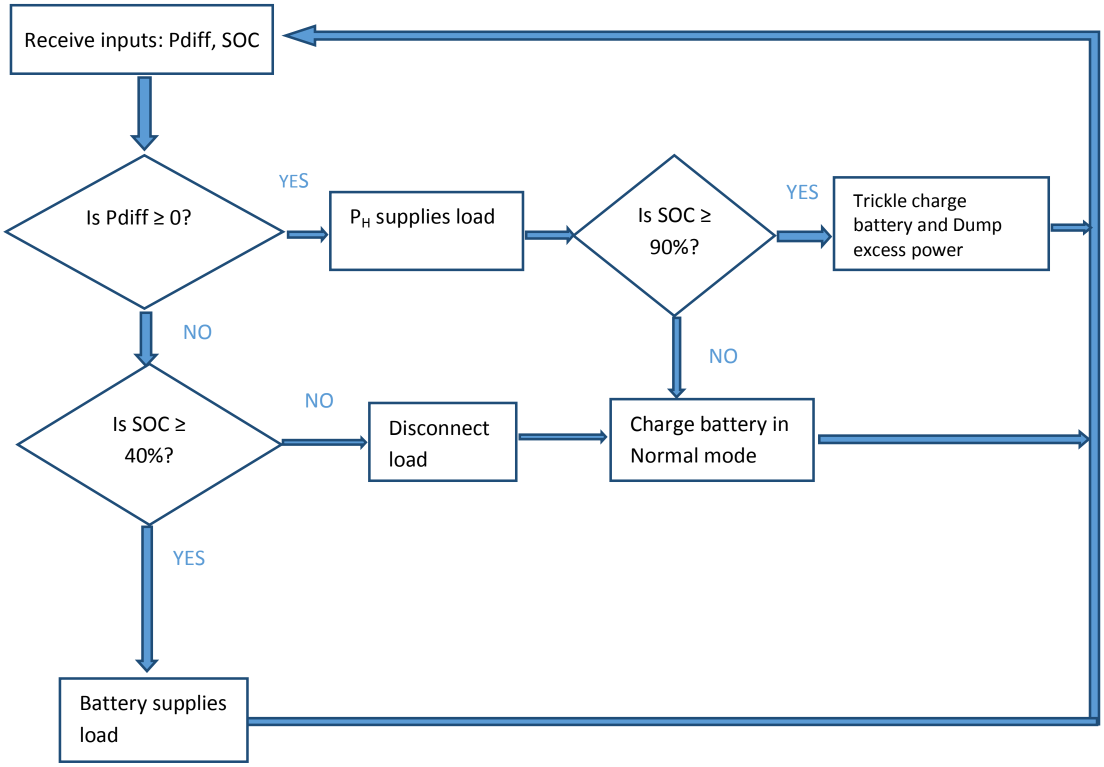


Fig. 2. Flow chart for power flow management

materials on energy flow management in hybrid renewable energy systems. Also, one of the authors of this work, being an authority on renewable energy systems, contributed his expertise.

2.2.1.1 Inputs and outputs

Fig. 3 shows the features and stages in the development of the fuzzy logic controller. The first step in designing the FLC was to define the inputs and outputs to the fuzzy system. The converters were treated as black boxes from which necessary terminals were drawn and connected to the controller for the purpose of system power management. The inputs to the FLC are "Power Difference" (difference between the total generated power (PV and WTG) and load demand), and "SOC". The first output is "Battery Status" which signals when to charge or discharge the battery, as well as which battery charging scheme should be employed. The second output is "Load Status" which is the signal that determine whether to connect or disconnect the load.

2.2.1.2 Linguistic description (variables and values)

Linguistic variables were used to describe each of the time-controller inputs and outputs. They are as follows:

"Pdiff" describes Power Difference
"SOC" describes State-of-Charge
"Lstatus" describes Load Status and
"Bstatus" describes Battery status

The linguistic values corresponding to the linguistic variables were given as: HIGH, NORM, and LOW for Pdiff and SOC. The linguistic values for Lstatus are ON and OFF, and which stand for 'connect load' and 'disconnect load' respectively. The linguistic values for Bstatus are CB, DB, and TC, which represent Charge Battery, Discharge Battery, and Trickle Charge Battery respectively. The "Charge Battery" and "Trickle Charge Battery" are the battery charging scheme/mode.

2.2.1.3 Rules

Linguistic quantifications were used to specify a set of rules to be used by the fuzzy inference

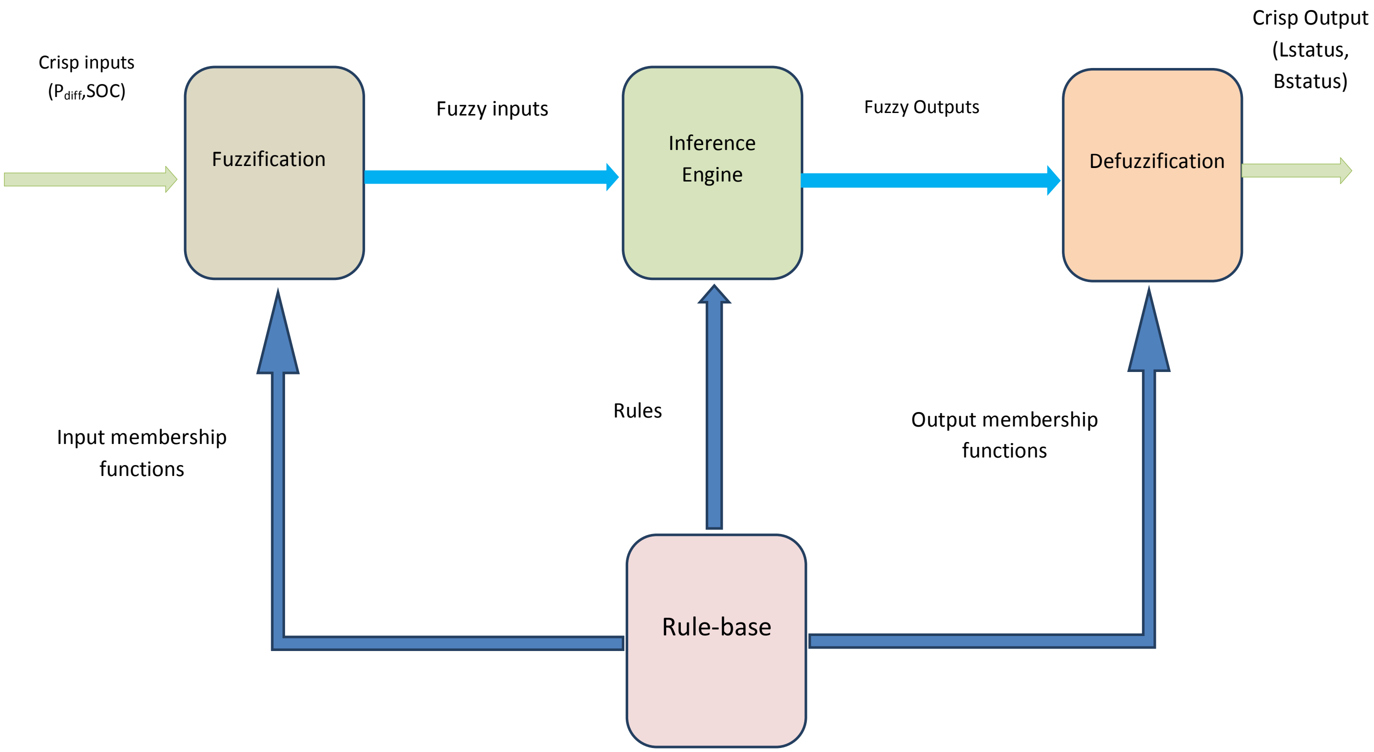


Fig.3. Fuzzy logic control diagram

engine. The rule-base had to be expanded to enable the implementation of the logic for disconnecting the load from the supplies when the need arises. The list of rules developed were presented (see section 3.3).

2.2.1.4 Membership functions

Membership functions which are used to quantify the meaning of linguistic values were constructed for each of the linguistic variables. The triangular membership function was used for the inputs and output membership functions.

2.2.1.5 Fuzzification, inference, and defuzzification

The crisp inputs are fuzzified, thereby obtaining the numeric values of the membership functions so defined. In the inference stage, the evaluations of the fuzzy rules and the combination of the results of the individual rules are performed. The minimum operator was used in this case. For the defuzzification process, the fuzzy values obtained from the inference engine are defuzzified to obtain crisp outputs. The centroid approach was employed in this stage.

2.2.2 System design

The control system was designed using MATLAB software. The rule-base proposed by Mamdani was employed. The Fuzzy logic toolbox and its Graphics User Interface (GUI) were used to define the inputs and outputs, define the linguistic variables and values as well as to construct the membership functions and for specifying the fuzzy set operators and implication, aggregation, and defuzzification methods. In addition, surface plots for the controller were generated using the MATLAB software.

3. RESULTS AND DISCUSSION

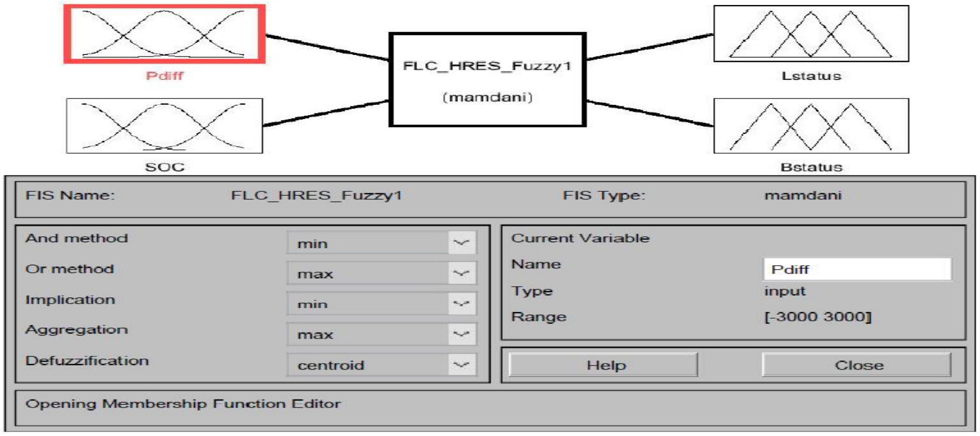
3.1 Inputs and Outputs

The inputs to the FLC were Pdiff (power difference between the hybrid power supply and load demand), and battery SOC whereas the outputs from the FLC were the Load Status and Battery Status. The “Battery Status” output indicated voltage signal levels for triggering either of the following functions: “discharge battery (DB)”, “charge battery (CB)”, or “trickle charge battery (TC)”. Whereas the “Load Status” output represented signal levels for activating either of the two functions “disconnect load (OFF)” or “connect load (ON)”.

The snapshot in Fig. 4 shows the specification of the inputs and outputs on MATLAB. Also indicated are the ‘min’ operator for the AND method and Implication, the ‘max’ for the aggregation, and the centroid approach for the defuzzification method.

3.2 Membership Functions

Triangular membership functions were used for all the input and output variables in this work. Hit and trial technique was used to develop the membership functions on MATLAB.



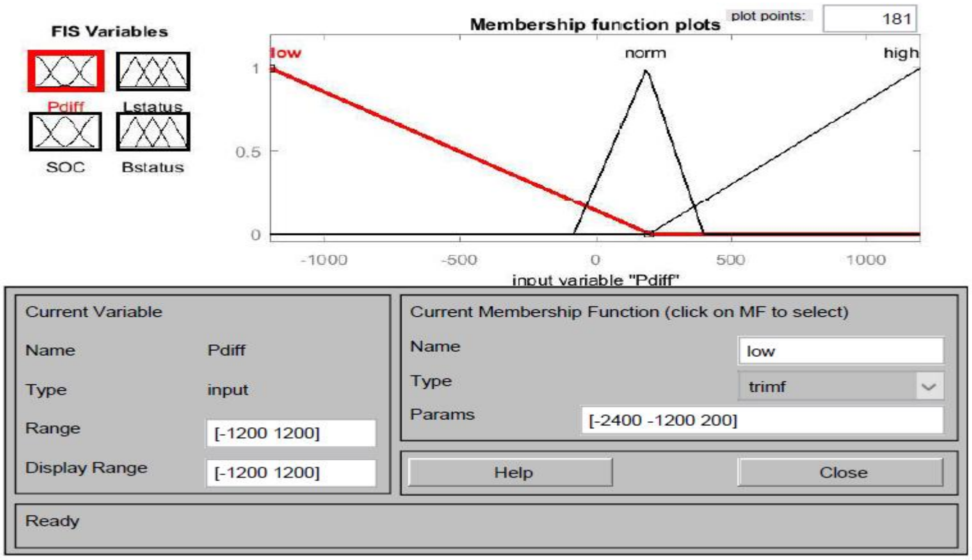
FIS Name: FLC_HRES_Fuzzy1
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: Pdiff
Type: input
Range: [-3000 3000]
Opening Membership Function Editor

Fig. 4. Snapshot on MATLAB showing FLC inputs and outputs, and, Implication, and aggregation methods, and defuzzification approach

Fig. 5 to Fig. 8 are snapshots from MATLAB showing the input and output membership functions for the fuzzy logic controller. In Fig. 5, three membership function curves are shown for the input variable Pdiff for “low”, “norm”, and “high” linguistic terms. The universe of discourse is the range in watts of the difference between supply power and load demand.

Fig. 6 shows the membership functions developed for the input variable “SOC” for the linguistic terms “low”, “norm”, and “high”. The elements of the universe of discourse are various percentages of the battery state-of-charge.

Fig. 7 is a snapshot from MATLAB showing the membership function plots for the output variable “Lstatus”. The universe of discourse is the range of voltage signals that should trigger either the “off” or “on” which disconnects or connects the load respectively. Signal levels between 0 and 1 will enable the “OFF” function, while signal levels between 1 and 2 will enable the “ON” status.

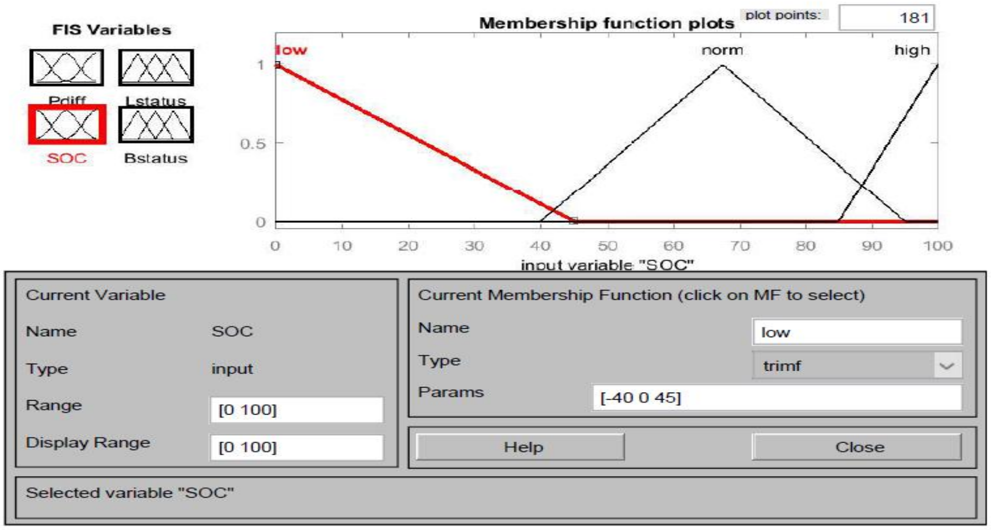


Current Variable
Name Pdiff
Type input
Range [-1200 1200]
Display Range [-1200 1200]

Current Membership Function (click on MF to select)
Name low
Type trimf
Params [-2400 -1200 200]

Ready

Fig. 5. Pdiff membership functions



Current Variable
Name SOC
Type input
Range [0 100]
Display Range [0 100]

Current Membership Function (click on MF to select)
Name low
Type trimf
Params [-40 0 45]

Selected variable "SOC"

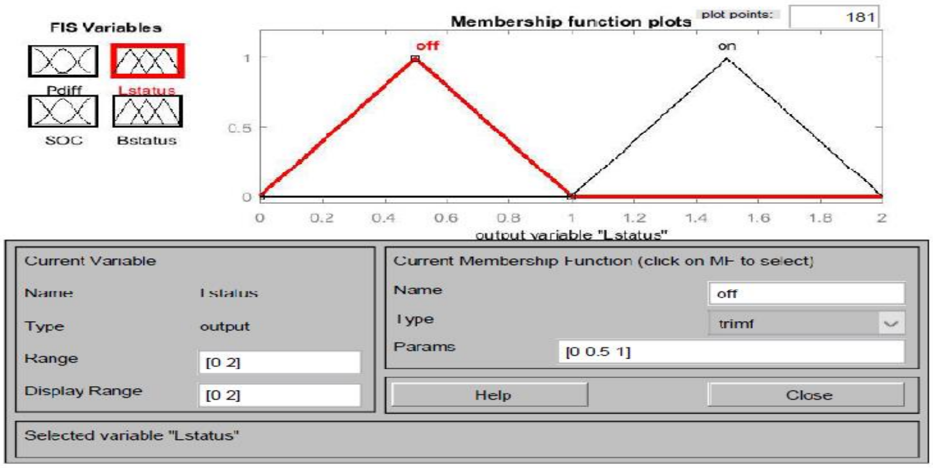
Fig. 6. SOC (%) membership functions

Fig. 8 shows the membership function plots for the output variable “Bstatus”. The universe of discourse is the range of voltage signals that should trigger either the “DB”, “CB”, or “TC” which should discharge the battery to meet the load demand, charge battery or trickle charge the battery respectively. Signal levels between 0 and 1 will enable the “DB” status, and signals between 1 and 2 will enable the “CB” status, while signals between 2 and 3 will trigger the “TC” status.

3.3 Rule-base

The rules to be used by the inference engine were developed and are listed below.

1. If Pdiff is LOW AND SOC is LOW THEN Lstatus is OFF AND Bstatus is CB
2. If Pdiff is LOW AND SOC is NORM THEN Lstatus is ON AND Bstatus is DB
3. If Pdiff is LOW AND SOC is HIGH THEN Lstatus is ON AND Bstatus is DB
4. If Pdiff is NORM AND SOC is LOW THEN Lstatus is ON AND Bstatus is CB
5. If Pdiff is NORM AND SOC is NORM THEN Lstatus is ON AND Bstatus is CB
6. If Pdiff is NORM AND SOC is HIGH THEN Lstatus is ON AND Bstatus is TC
7. If Pdiff is HIGH AND SOC is LOW THEN Lstatus is ON AND Bstatus is CB
8. If Pdiff is HIGH AND SOC is NORM THEN Lstatus is ON AND Bstatus is CB
9. If Pdiff is HIGH AND SOC is HIGH THEN Lstatus is ON AND Bstatus is TC

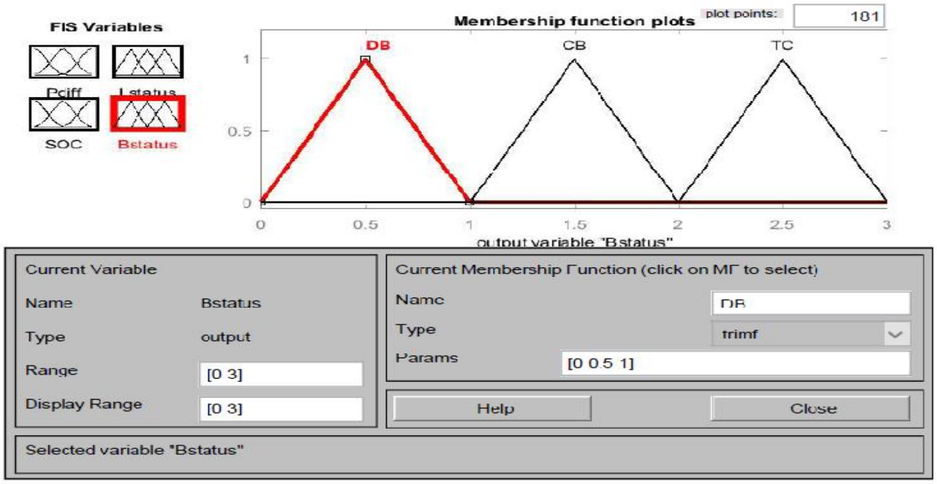


Current Variable
Name Lstatus
Type output
Range [0 2]
Display Range [0 2]

Current Membership Function (click on MF to select)
Name off
Type trimf
Params [0 0.5 1]

Selected variable "Lstatus"

Fig. 7. Lstatus membership functions



Current Variable
Name Bstatus
Type output
Range [0 3]
Display Range [0 3]

Current Membership Function (click on MF to select)
Name DB
Type trimf
Params [0 0.5 1]

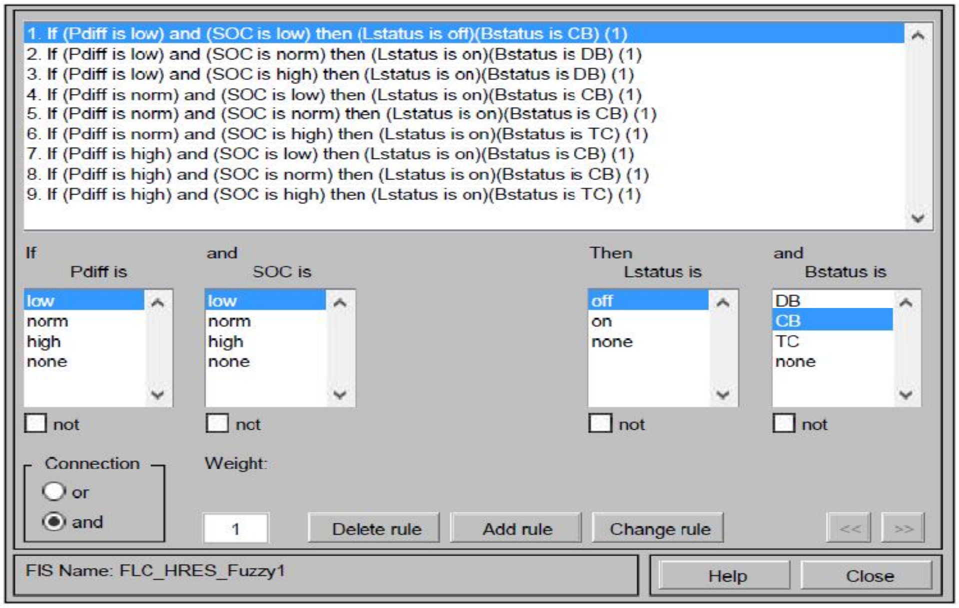
Selected variable "Bstatus"

Fig. 8. Bstatus membership functions

The snapshot of the rule-base as designed on MATLAB is shown Fig.9. The rule-base shows the integration of the logic for the dedicated output for turning off the load should the conditions be met.

Figs. 10 and 11 show the surface plots generated for the output variables “Bstatus” and “Lstatus” respectively. The surface plots show the overall behavior of the system at a glance.

The fuzzy logic controller presented in this work gives the advantage of ease of design. There is no need for tedious mathematical modelling of the system as required in control techniques like proportional and integral controllers. There was also no need for extra devices to implement the



1. If (Pdiff is low) and (SOC is low) then (Lstatus is off)(Bstatus is CB) (1)
2. If (Pdiff is low) and (SOC is norm) then (Lstatus is on)(Bstatus is DB) (1)
3. If (Pdiff is low) and (SOC is high) then (Lstatus is on)(Bstatus is DB) (1)
4. If (Pdiff is norm) and (SOC is low) then (Lstatus is on)(Bstatus is CB) (1)
5. If (Pdiff is norm) and (SOC is norm) then (Lstatus is on)(Bstatus is CB) (1)
6. If (Pdiff is norm) and (SOC is high) then (Lstatus is on)(Bstatus is TC) (1)
7. If (Pdiff is high) and (SOC is low) then (Lstatus is on)(Bstatus is CB) (1)
8. If (Pdiff is high) and (SOC is norm) then (Lstatus is on)(Bstatus is CB) (1)
9. If (Pdiff is high) and (SOC is high) then (Lstatus is on)(Bstatus is TC) (1)

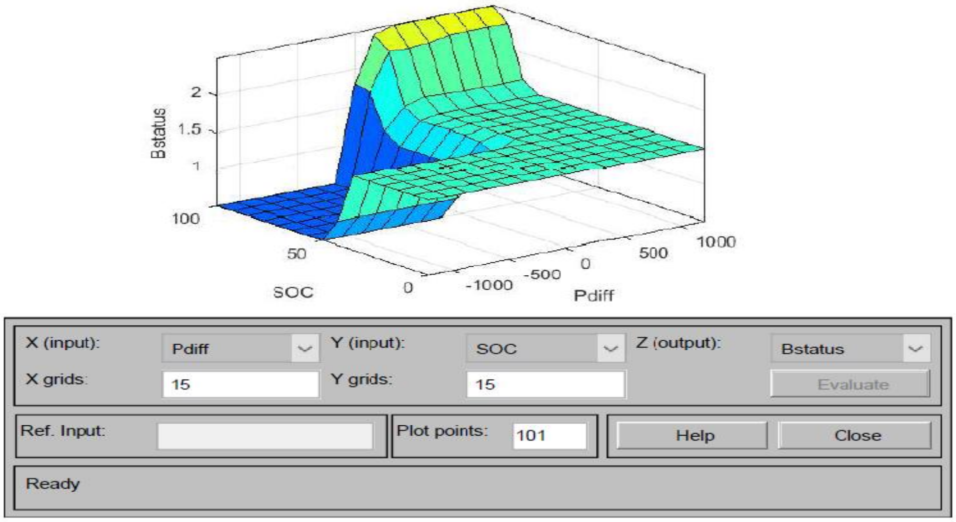
If Pdiff is	and SOC is	Then Lstatus is	and Bstatus is
low	low	off	DB
norm	norm	on	CB
high	high	none	TC
none	none		none
☐ not	☐ not	☐ not	☐ not

Connection: ○ or ● and

Weight: 1

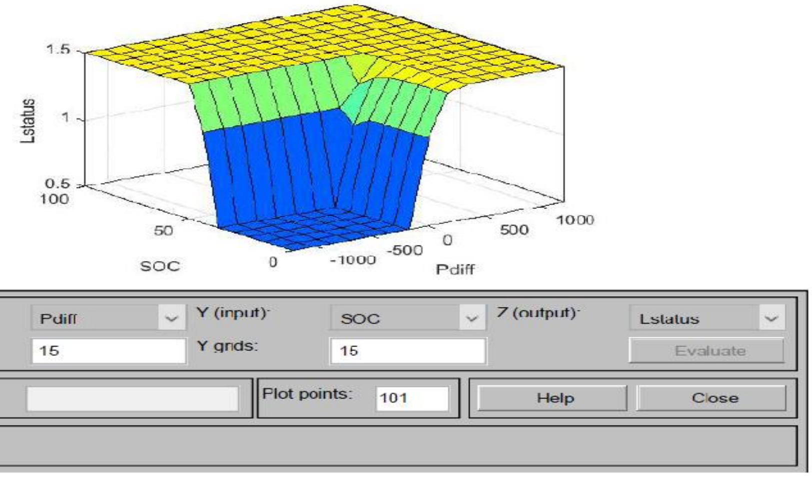
FIS Name: FLC_HRES_Fuzzy1

Fig. 9.Rule-base on MATLAB



X (input): Pdiff
Y (input): SOC
Z (output): Bstatus
X grids: 15
Y grids: 15
Ref. Input:
Plot points: 101
Ready

Fig. 10. Surface plot for Bstatus



X (input): Pdiff
X grids: 15
Y (input): SOC
Y grids: 15
Z (output): Lstatus
Ref. Input:
Plot points: 101
Ready

Fig. 11. Surface plot for Lstatus

logic for load control in the event of insufficient power from the hybrid source and low SOC since the logic for cutting off the load was integrated into the FLC.

4. CONCLUSION

This work presents the development of a power management controller based on the fuzzy logic control which can be used in a hybrid renewable energy system. This work showed that the use of fuzzy logic control in energy flow management in hybrid renewable energy systems gives the advantage of ease of design of the control system since there is no need to develop complex mathematical models as required in conventional control techniques: the fuzzy inference system simply emulates and automates the expert's decision making for the system behavior. The controller features a dedicated function for turning off the system when the conditions are met, thereby ensuring longer battery life as well as the overall safety of the system. With an easy-to-develop control design, one achieves a better cost-effective solution.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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