International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 03 March 2025
Page No: 812-819
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0114

Fuzzy Logic Based Energy Management System for Grid Connected Solar PV System

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Abstract
Expanding access to electricity continues to be a significant problem, especially in rural and remote areas, due to geographical and infrastructure constraints that impair power supply reliability. A sustainable solution for the same is the incorporation of renewable energy sources, including photovoltaic (PV) systems. However, the intermittent nature of solar put an emphasis on need of an efficient energy management system, to optimize generation and consumption. A rule-based fuzzy logic controller (FLC) for an energy management system (EMS) in a grid-connected photovoltaic system is proposed in this work. With the help of fuzzy logic control for intelligent decision-making, alternates between available power sources, maximizes energy extraction from renewable source generation, and reduces reliance on grid supply. This allows for effective power demand management, improves operational efficiency, contributes to economic and environmental benefits.
Keywords: *Photovoltaic System, Fuzzy Logic Controller, Energy Management System.*

1. Introduction
Due to technological advancement, industrialization, our entire life is around electricity, which results in rapidly increasing power demand worldwide, and the rate of increase in power demand is much greater than rate of increase in generation, i.e; available generation is inadequate to meet rapidly growing demand, a sustainable solution for the same is incorporating renewable energy sources in the power system. There's a high penetration/incorporation of renewable energy sources worldwide, like solar system due to its several merits over conventional energy sources, only major issue is intermittency of supply, which puts an emphasis on need of an energy management system. There are different energy management system in which fuzzy logic controller has been used in different perspectives. Alankrita et al.[1] in order to maximize power exchange between the grid and renewable sources created a FLC for energy management in a grid-connected hybrid PV system. The study emphasized the benefits of handling uncertainty in energy generation and power demand by utilizing rule-based decision-making & linguistic factors. Zec & Malovic [2] in microgrid employed fuzzy logic to integrate PV systems, battery storage, and feed-in tariff, highlighted how well fuzzy-based load management stabilizes the power supply under different load scenarios. Pan et al. [3] taking into account flat & time-of-use power pricing, energy management in grid-connected with PV & battery storage. The energy storage choices optimized by fuzzy logic-based EMS, which guaranteed economic power use while preserving grid stability. Nebey and Honrubia-Escribano [4] optimized energy exchange between the PV system, battery, and grid by implementing an EMS using MATLAB simulation. The research showed that fuzzy rule-based controllers could effectively switch between energy sources, enhancing system performance. Vivas et al. [5] this strategy combined fuzzy-based EMS for microgrids with hydrogen energy storage. According to research, fuzzy controllers could efficiently control a variety of energy sources while lowering operating expenses. Faqih et al. [6] investigated a smart grid photovoltaic

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system with mamdani fuzzy logic control, in which energy management choices were dependent on battery state of charge and sunshine intensity. The viability of fuzzy logic in real-time applications was confirmed by their pilot-scale deployment Al-Sakkaf et al. [7] integrated economic dispatch factors into their optimization of fuzzy-based EMS for autonomous dc microgrids. The system demonstrated the adaptability of fuzzy logic in dynamic energy contexts by effectively balancing economic considerations, grid interaction, and renewable energy generation. Uddin & Islam [8] proposed a real-time fuzzy-based smart EMS that integrates batteries, the grid, and renewable energy sources, which demonstrated the best power flow choices, guaranteeing the highest possible use of the energy supply while preserving grid stability. Arcos-Aviles et al. [9] created a fuzzy-based EMS that maximizes power distribution among PV, batteries, and the grid, fuzzy logic controllers' scalability and adaptability for a range of home energy demands were highlighted in their study. Hussain et al. [10] showed how fuzzy logic may be used to operate battery energy storage systems and increase the resilience of hybrid microgrids, demonstrated the significance of fuzzy controllers in controlling battery charge/discharge cycles, guaranteeing a steady power supply in hybrid energy networks. Singh and Vandana [11] for standalone PV systems, used fuzzy-based control models for rural home energy management in India. The strategy improved the efficiency and sustainability of solar-powered rural electrification by effectively optimizing energy distribution. The present work proposed rule based fuzzy logic controller which is an effective solution for energy management system for grid connected photovoltaic system, dynamically switching between available source of generation- Solar or grid supply, in response to particular time of use- day or night, and power demand, aims at extracting maximum of energy from renewable source, ensure the reliability of power supply. The paper is organized as follows: Section 2 explain Fuzzy logic in brief. Section 3 presents the proposed methodology of fuzzy logic controller and the results are presented in the section 4.

2. Fuzzy Logic

Uncertainty is significant challenge in decision making & problem solving, many decision-making and problem-solving tasks are too complex to be defined precisely. Most words & evaluations we use in our daily reasoning are not clearly defined in a mathematical manner. Two broad categories of methods currently in use to solve problem of uncertainty are probabilistic statistical techniques - which rely on probability theory and statistical analysis, useful when there's sufficient historical data to estimate different outcomes & another method is non-probabilistic- which doesn't depend on probability, includes fuzzy logic, default logic, dempster shafer theory of evidence, endorsement based system, qualitative reasoning; among these fuzzy logic is widely used. Fuzzy refers to something that is not clear, vague, imprecise, includes noisy or missing input information. Fuzzy Logic resembles human reasoning in its use of approximate information and uncertainty to generate decisions, i.e; Fuzzy logic is a way to represent variation or imprecision in logic and way to make use of natural language (linguistic variable) in logic, use approximate reasoning rather than exact modes of reasoning. It is an extension of multi-valued logic, where everything including truth is a matter of degree, rather than fixed absolute. Fuzzy logic is a convenient way to map an input space to an output space. Prof. Lotfi Zadeh, at University of California at Berkeley, first presented fuzzy logic in the mid-1960's. The first practical application of fuzzy logic was in 1974 when Mamdani and Asselin used fuzzy logic to regulate a steam engine. In 1985 researchers at Bell laboratories developed first fuzzy logic chip.

Classical logic is bivalent logic having its roots in classical set theory also termed as crisp set theory, crisp variables handle only 0's and 1's, implying that every proposition is either true or false, allowing no intermediate values, example- speed is slow(0) or fast(1). Spanning range is small, making it less adaptable to real world complexities. Just as Boolean logic has its roots in theory of crisp set, fuzzy logic has roots in the theory of fuzzy set, fuzzy variables handle all intermediate values between 0 & 1, example- speed is slowest (0-0.25), slow (0.25-0.50), fast (0.50-0.75), fastest (0.75-1). A fuzzy set is without clearly defined boundary. It contain variables with only a partial degree of membership. Fuzzy sets deals with imprecision in information. Fuzzy Logic is conceptually easy to understand. It is easy to design a rule-based controller based on combination of linguistic and mathematical variables. It deals with imprecision or uncertainty in information. It is based on natural language. Nonlinear functions of any complexity can be modeled by it. Fuzzy logic can be used together with conventional control methods. Due to its several advantages like there's no need for a mathematical model, it provides smooth transition between members and nonmembers, relatively its simple, fast and adaptive; less sensitive to system fluctuations, it puts an emphasis on need of Fuzzy logic. Japan is the world's leading producer of fuzzy based commercial applications, and in our country India also has been actively exploring fuzzy logic application in various sectors- particularly in engineering, automation, artificial intelligence, medical diagnosis, weather prediction, track management, etc. With the rise of industy4.0, India continues to adopt fuzzy logic. The research institutes have contributed to advancements in fuzzy logic based control systems, making India a key player in global advancements of this technology.

3. Method

3.1. Design of Fuzzy Logic Controller

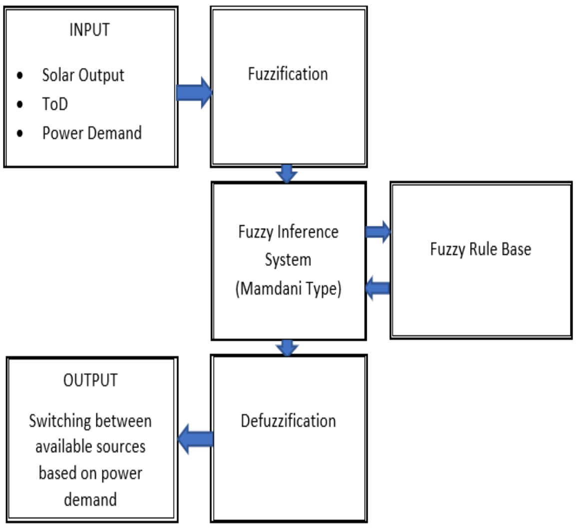

Figure 1 Block Diagram of Fuzzy Logic Controller for On-Grid Solar System

Using Fuzzy Logic Toolbox in MATLAB software, we can create and modify fuzzy inference systems. Fuzzy Logic Controller (FLC) is a system that mimics human decision-making by handling uncertain or imprecise information. It is widely used in various control applications where precise mathematical models are difficult to define. FLC consists of four main parts-

1. Fuzzification
2. Fuzzy Rule base
3. Fuzzy Inference system
4. Defuzzification

1. **Fuzzification** is a process by which crisp input are convert in fuzzy input (a linguistic variables), i.e; each input value converted into a membership value for each input, and output of fuzzification is degree of membership corresponding to input. Range of possible values for input & output variables are determined, Fuzzy logic toolbox consist 11 built-in membership function types, among these triangular membership function (trimf) is used in present work.
2. **Fuzzy rule** is defined as a IF and THEN conditional statement, map an input space to an output space.
3. **Fuzzy Inference** is mapping given fuzzy input to a fuzzy output, based on which decisions can be made. Two types of fuzzy inference systems are: Mamdani-type and Sugano-type, Mamdani type fuzzy inference system is used in present work.
4. **Defuzzification-** The process converts fuzzy output into crisp output. Figure.1 presents the block diagram of fuzzy logic controller for an on-grid solar PV system, showing its key components which processes the input variables and provides desired output, i.e; dynamically switches between available sources-power from solar output, grid supply, or combination of both, in response to inputs- solar output power availability, time of day, power demand.

3.2. Fuzzification of Input Variables

Fuzzification process involves converting numerical (crisp) values of input variables to FLC into fuzzy

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https://doi.org/10.47392/IRJAEH.2025.0114

(linguistic) values.

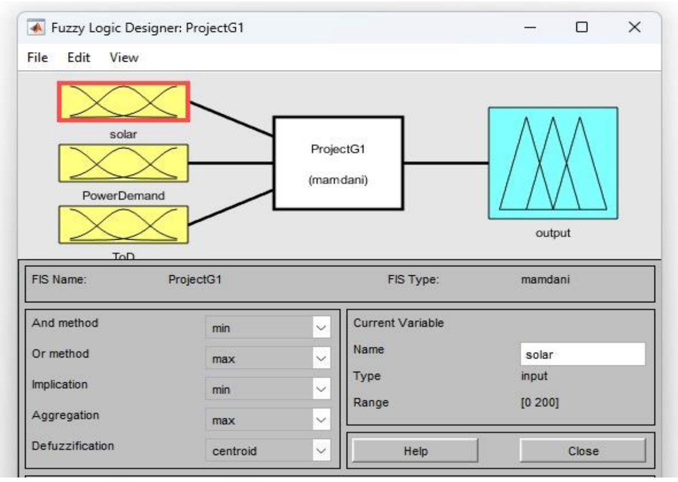

Figure 2 Fuzzy Inference System Editor of FLC for On-Grid Solar PV System

Fuzzy Inference System editor of FLC for on-grid solar PV system is shown in Figure 2. Mamdani type fuzzy inference system is used. In present study- solar generation, power demand, time of day are selected as the three input variables. Fuzzy Inference is process of mapping fuzzy input to fuzzy output.

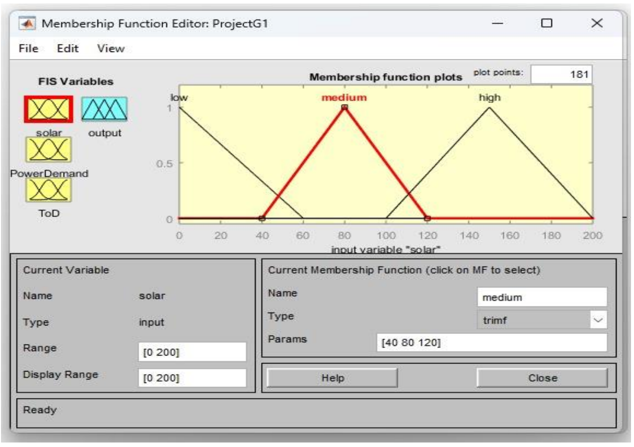

Figure 3 Membership Function Editor of Input Variable Solar PV System Generation

The membership function editor of the input variable Solar is shown in Figure 3, triangular membership function (trimf) is used. The fuzzy set for the solar generation are low, medium, high & ranges for the same are [-60, 0, 60] KW, [40, 80, 120] KW, [100, 150, 200] KW respectively. The overlap between sets is for smooth transition, enabling FLC to respond flexibly. Let PV represent the solar PV system generation in KW. The mathematical representation for the same is given by as shown in the Equation (1) to Equation (3).

$$\mu_{Low}(\text{PV}) = \begin{cases} 0 & if\ PV \leq -60\ or\ PV \geq 60 \\ \dfrac{PV+60}{60} & if -60 \leq PV \leq 0 \\ \dfrac{60-PV}{60} & if\ \ 0 \leq PV \leq 60 \end{cases}$$

$$\mu_{Medium}(\text{PV}) = \begin{cases} 0 & if\ PV \leq 40\ or\ PV \geq 120 \\ \dfrac{PV-40}{40} & if 40 \leq PV \leq 80 \\ \dfrac{120-PV}{40} & if\ \ 80 \leq PV \leq 120 \end{cases}$$

$$\mu_{High}(\text{PV}) = \begin{cases} 0 & if\ PV \leq 100 \\ \dfrac{PV-100}{50} & if\ 100 \leq PV \leq 150 \\ \dfrac{200-PV}{50} & if\ \ 150 \leq PV \leq 200 \end{cases}$$

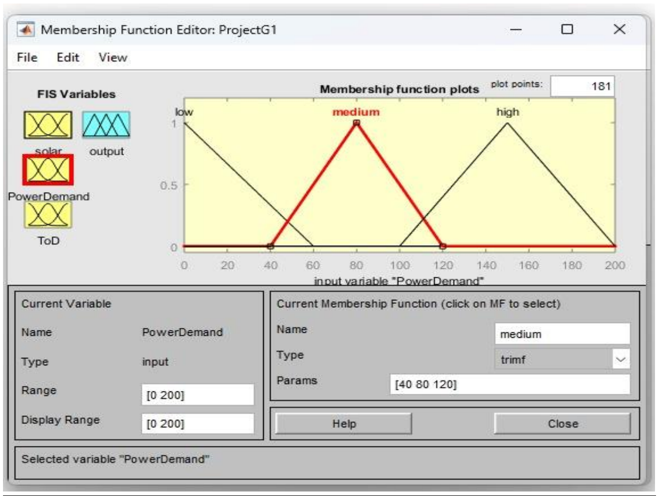

Figure 4 Membership Function Editor of Input Variable Power Demand

The membership function editor of the input variable power demand is shown in Figure 4, triangular membership function (trimf) is used. The fuzzy set for the power demand are low, medium, high & ranges for the same are [-60, 0, 60] KW, [40, 80, 120] KW, [100, 150, 200] KW respectively. The overlap between sets is for smooth transition, enabling FLC to respond flexibly. Let PD represent the power

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https://doi.org/10.47392/IRJAEH.2025.0114

demand in KW. The mathematical representation for the same is given by as shown in Equation (4) to Equation (6).

$$\mu_{Low}\,(\mathrm{PD})=\begin{cases} 0 & if\ PD\ \leq -60\ or\ PD \geq 60 \\ \dfrac{PD+60}{60} & if -60 \leq PD \leq 0 \\ \dfrac{60-PD}{60} & if\ \ 0 \leq\ PD \leq 60 \end{cases}$$

$$\mu_{Medium}\,(\mathrm{PD})=\begin{cases} 0 & if\ PD\ \leq 40\ or\ PD \geq 120 \\ \dfrac{PD-40}{40} & if 40 \leq PD \leq 80 \\ \dfrac{120-PD}{40} & if\ \ 80 \leq\ PD \leq 120 \end{cases}$$

$$\mu_{High}\,(\mathrm{PD})=\begin{cases} 0 & if\ PD\ \leq 100 \\ \dfrac{PD-100}{50} & if\ 100 \leq PD \leq 150 \\ \dfrac{200-PD}{50} & if\ \ 150 \leq\ PD \leq 200 \end{cases}$$

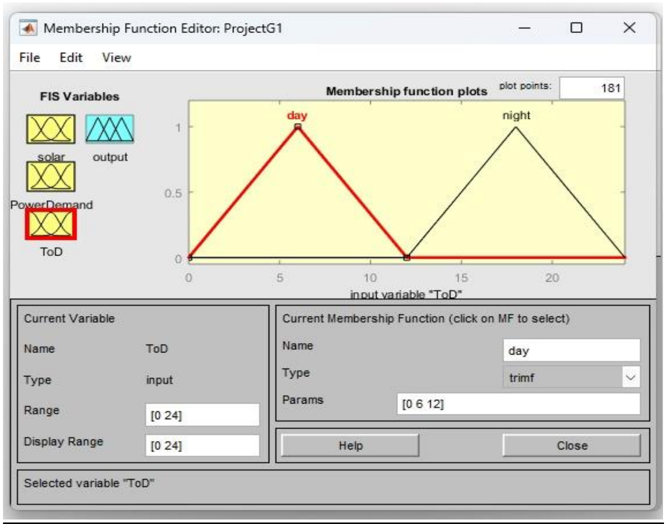

Figure 5 Membership Function editor of input Variable Time of Day

The membership function editor of the input variable time of day (ToD) is shown in Figure 5, triangular membership function (trimf) is used. The fuzzy set for time of day are day & night, and ranges for the same are [0, 6, 12], [12, 18, 24] respectively. Let ToD represent the time of day. The mathematical representation for the same is given by as shown in Equation (7) & Equation (8).

$$\mu_{Day}\,(\mathrm{ToD})=\begin{cases} 0 & if\ ToD\ \leq 0\ or\ ToD \geq 12 \\ \dfrac{ToD}{6} & if\ 0 \leq ToD \leq 6 \\ \dfrac{12-ToD}{6} & if\ \ 6 \leq\ ToD \leq 12 \end{cases}$$

$$\mu_{Night}\,(\mathrm{ToD})=\begin{cases} 0 & if\ ToD\ \leq 12\ or\ ToD \geq 24 \\ \dfrac{ToD-12}{6} & if 12 \leq ToD \leq 18 \\ \dfrac{24-ToD}{6} & if\ \ 18 \leq\ ToD \leq 24 \end{cases}$$

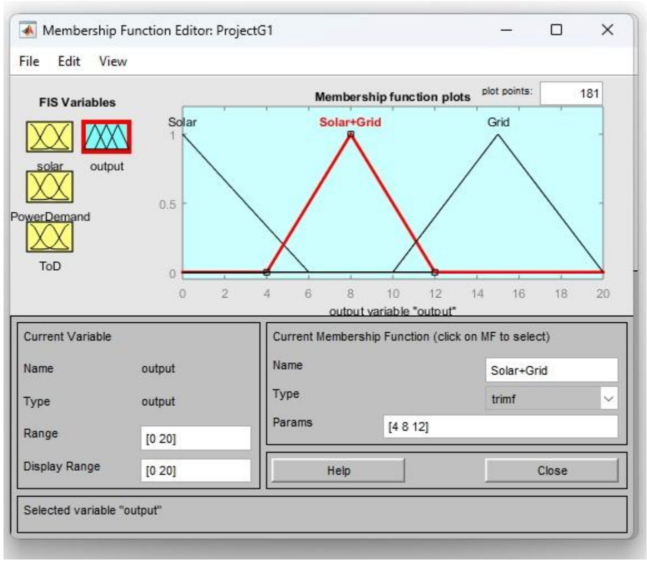

Figure 6 Membership Function Editor of Output Variable

The membership function editor of the output variable is shown in Figure 6, triangular membership function (trimf) is used. The fuzzy set for the output are solar, solar+grid, grid & ranges for the same are [-6, 0, 6] , [4, 8, 12] , [10, 15, 20] respectively. The overlap between sets is for smooth transition, enabling FLC to respond flexibly. Let OUT represent the output. The mathematical representation for same is given as shown in Equation (9) to Equation (11).

$$\mu_{Solar}\,(\mathrm{OUT})=\begin{cases} 0 & if\ OUT\ \leq -6\ or\ OUT \geq 6 \\ \dfrac{OUT+6}{6} & if -6 \leq OUT \leq 0 \\ \dfrac{6-OUT}{6} & if\ \ 0 \leq\ OUT \leq 6 \end{cases}$$

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$$\mu_{Solar+Grid}\,(\mathrm{OUT}) = \begin{cases} 0 & if\ OUT\ \le 4\ or \ge 12 \\ \dfrac{OUT-4}{4} & if 4 \le OUT \le 8 \\ \dfrac{12-OUT}{4} & if\ \ 8 \le\ OUT \le 12 \end{cases}$$

$$\mu_{Grid}\,(\mathrm{OUT}) = \begin{cases} 0 & if\ OUT\ \le 10 \\ \dfrac{OUT-10}{5} & if\ 10 \le OUT \le 15 \\ \dfrac{20-OUT}{5} & if\ \ 15 \le\ OUT \le 20 \end{cases}$$

Table 1 Different Possible Probabilistic Combination Based on Input to Fuzzy Logic Controller, For Design of Fuzzy Rule-Base

Solar	ToD	Power Demand	Output
Low	Day	Low	Solar
Low	Day	Medium	Solar+Grid
Low	Day	High	Solar+Grid
Medium	Day	Low	Solar
Medium	Day	Medium	Solar
Medium	Day	High	Solar+Grid
High	Day	Low	Solar
High	Day	Medium	Solar
High	Day	High	Solar+Grid
Nil	Night	Low	Grid

Table 1 shows several probabilistic combinations of input variables, for the purpose of creating a fuzzy rule base for an energy management system. Fuzzy rule editor of FLC for an on-grid solar system is shown in Figure 7, which shows the fuzzy rules- if and then conditional statements formed from different possible probabilistic combination of input variables as shown in Table 1.

- **Rule 1:** Low solar power can meet low demand without the need for grid backup.
- **Rule 2:** Low solar power is insufficient for medium demand and necessitates grid backup.
- **Rule 3:** Low solar power cannot meet high demand on its own, hence grid power is required.
- **Rule 4:** Medium-sized solar power plants can meet low demand without relying on the grid.
- **Rule 5:** Medium solar power can entirely supply medium demand in the absence of grid support.
- **Rule 6:** High demand necessitates additional grid electricity, despite moderate solar availability.
- **Rule 7:** High solar power is more than sufficient to meet low demand efficiently.
- **Rule 8:** High solar power can supply medium demand without using the grid.
- **Rule 9:** Despite the abundance of solar energy, grid electricity is essential to avoid overload.
- **Rule 10:** Because solar power is absent at night, the grid provides electricity.

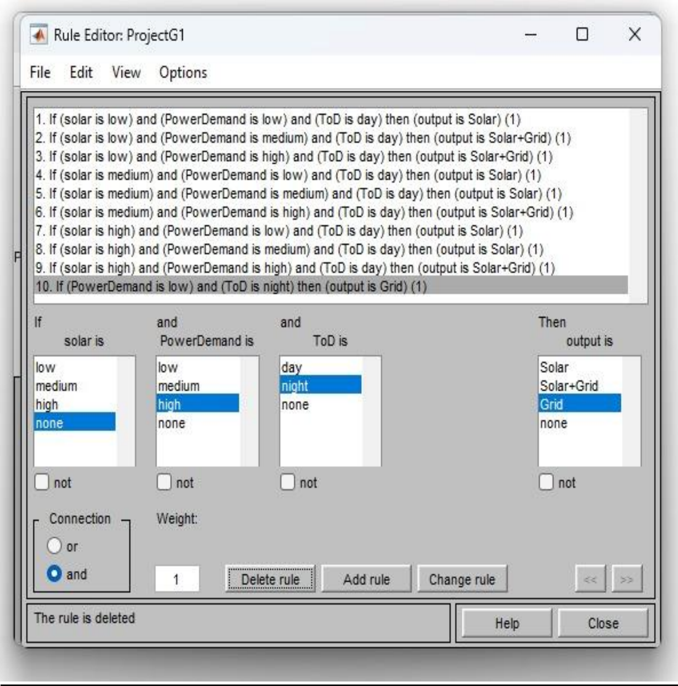

Figure 7 Fuzzy Rules Editor of FLC

4. Results and Discussion

The present work proposed rule based Fuzzy Logic Controller which is an effective solution for Energy Management system for grid connected Photovoltaic System with battery, dynamically switching between available source and generation at particular time, extracting maximum of energy from Renewable source, ensure reliability of supply, also aims at power demand management. To ensure that the suggested Fuzzy Logic Controller (FLC) for a grid-connected solar PV system, is efficient in decision-making, switching between available source, based on solar power availability, power demand, and time of day. To see how input conditions affect the controller's decision, the Rule Viewer tool is used.

4.1. Result

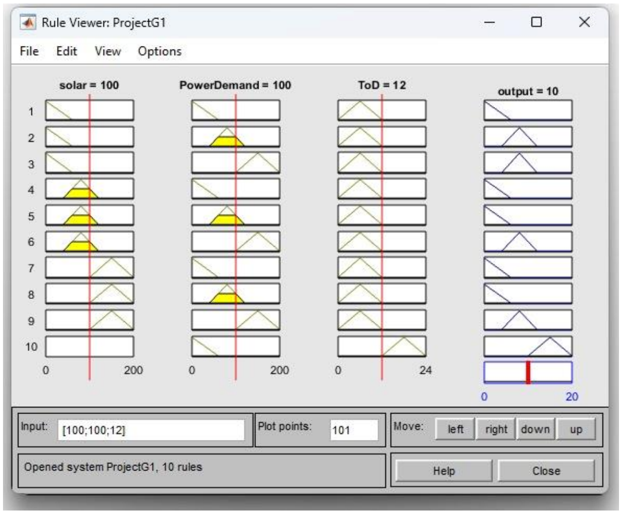

Figure 8 Fuzzy Rule Viewer

4.2. Result Discussion

To validate the effectiveness of the proposed Fuzzy Logic Controller (FLC) in optimizing energy source selection for a grid-connected solar PV system, the system was analyzed under different conditions of solar power availability, power demand, and time of day (ToD). Rule viewer represents how the input conditions affect the controller's decision/ output, The yellow highlighted region's on fuzzy rule viewer indicates that which fuzzy rules are activate, as here multiple rules contributes to output. As rule viewer indicates solar power is (100), since solar power is available, ToD is (12) during noon/day time when there's significant power demand (100), the result validates that the fuzzy rules are correctly formulated and applied, as the output value (10) lies in range [4, 8, 12] represents the output (solar+grid), to primarily use power supply from solar and if additional power needed can be taken from grid supply. Similarly, when there's significant generation of solar power and there's low power demand, can be met by Solar power. And during night hours when there's no solar generation, the power demand can be meet by grid supply to ensure reliability of power supply. Thus, the results hows the effectiveness of proposed FLC, shown in Figure 8.

Conclusion

The Energy Management System (EMS) with Fuzzy Logic Control (FLC) improves energy efficiency by intelligently switching loads between available sources. This lowers grid dependence by maximum utilisation of energy from renewable energy, resulting in a balanced demand-supply system, improves efficiency and reliability of power supply.

Acknowledgements

We express our deep gratitude to everyone who directly or indirectly contributed in this work, with their guidance and motivation. Our heartfelt thanks go to our parents for their love, support, and belief throughout this journey. Lastly, we extend our gratitude to our friends for their encouragement, assistance, for celebrating our achievements together.

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