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FUZZY LOGIC-BASED POWER MANAGEMENT IN GRID-CONNECTED SOLAR ENERGY SYSTEMS

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Abstract:
With the ever-increasing application of photovoltaic systems on the power grid, energy flow management and grid stability have become a key factor, especially under varying conditions like variable cloud cover and fluctuating load demands. The paper looks forward to proposing a fuzzy logic approach to the management of energy regarding a solar energy system connected to a grid, aiming at obtaining an optimised power distribution among PV generation, the grid, and battery storage. The proposed system will be driven by five input parameters, PV value, grid availability, load demand, battery state of charge, and tariff rate, to regulate the energy flow activity within different scenarios. The simulation results developed in the MATLAB Simulink environment proved the effectiveness of the applied controller in maintaining energy stability and fulfilling the requirements of a load within seven case studies for a 24-hour duration. The work points out the potential of fuzzy logic, besides reliability, in enhancing the efficiency of various renewable energy systems integrated with conventional energy supply grids.

Keywords: solar energy, fuzzy logic, power management, grid stability, photovoltaic systems

1. Introduction

This transition to renewable resources around the globe is essential in combating the increasing prices of fossil fuel, reducing carbon emissions, and ultimately meeting the growing demand for reliable and clean sources of energy. Solar photovoltaic systems, which convert sunlight directly into electricity, are increasingly popular since their impact on the environment is minimal, and they can be highly scalable. However, the

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integration of PV systems in the conventional grid system presents a number of obstacles where these systems contribute largely to the percentage contribution to the energy network. The variability in sunlight through the influences in weather conditions may be unstable, hence complicating the approach to balancing supply and demand, as indicated by Chalmers *et al.*, 1985.

Individual microgrids can be such a flexible and effective response to these challenges, using distributed energy resources like PV panels, fuel cells, and wind turbines, along with energy storage options like batteries. Microgeneration techniques, first proposed by Asano *et al.* in 1996, are providing increased flexibility for both the utilisation and generation of energy independent of and interconnected with larger electric power networks. This kind of grid stability with high-penetration PV systems is contingent upon an advanced energy management system to offset in real time the fluctuations that occur with supplies and demand.

In this work, an application of the power management FLC is proposed for a grid-connected PV system. Fuzzy logic, originally developed by Zadeh in 1965, allows the treatment of uncertainty and, in addition, provides variable continuous adjustments according to a range of input values, while in traditional binary logic, the decisions are discrete. This adaptability is especially useful when dealing with renewable energy resources since the variability of environmental conditions, load changes, and the levels of energy storage are different at every time of day (Jewell *et al.*, 1988). The proposed five input parameters in the system here, such as PV output, grid availability, load demand, battery SOC, and tariff rate, are processed by a fuzzy logic controller for dynamically balancing energy usage among PV, battery storage, and grid power sources.

2. Fuzzy Logic Advantages for High-Penetration PV Systems

The energy management function identified in a fuzzy logic controller optimises the performance by dynamically readjusting for every load change, grid availability, and real-time environmental data. This adaptive control technique provides voltage stability that grants limited dependence on grid power during high-tariff periods. It further minimises the common problems that are typical of high-penetration PV environments: voltage sags and power fluctuation (Baran *et al.*, 2012; Alam *et al.*, 2014). s. Owing to this fact, the fuzzy logic controllers will indubitably prove to be robust solutions for the integration of renewable energy resources in power grids to improve overall system reliability and efficiency.

3. Scope and Objectives of Study

With increased utilisation of PV Energy in distributed power networks, advanced mechanisms are required to control grid stability and optimise power flow. This work is on the demonstration of the benefits accruable from implementing a fuzzy logic-based power management system within a grid-connected PV system. The performance of the system is simulated, with the MATLAB Simulink, for a 24-hour performance under various scenarios, testing the capability of the controller to stabilise the energy flow and optimise costs given changing load and environmental tariff conditions.

4. Literature Review

While there is a rising demand for clean and sustainable energy, PV systems have become one of the most feasible alternatives because of their direct conversion of sunlight into electric energy while having little environmental impact. While integrating at high penetration levels into conventional grids, critical challenges arise in the integration; these are voltage instability, unbalanced loads, and a need for energy management systems that ensure affordable efficiency in maintaining stability within the grid (Jewell & Unruh, 1990). This review discusses, among others, previous work done on PV integration, the role of fuzzy logic in energy management, and the benefits and challenges associated with distributed generation systems.

4.1 Challenges in PV Integration into Power Grids

Studies indicate that operational challenges in PV systems are a result of variations in sunlight, which may cause frequent voltage sags, power imbalances, and even system instability in a high-penetration PV network. Chalmers *et al.* (1985) studied how PV generation can contribute to Shift Utility operations; given the highly variable nature of solar energy, their fluctuations complicate the utilities load-balancing problems during partial cloud cover or when sudden changes in irradiance occur. Accordingly, Jewell and Unruh (1990) quantified limits on cloud-induced PV fluctuations, which they brought out as having a strong impact on the stability and efficiency of the grid.

The challenges, in turn, trigger the fast development of Distributed Energy Systems, like microgrids and hybrid PV setups, with an aim to enhance energy supply reliability and reduce transmission losses. The two common methods of generation sources are PV, wind, and storage batteries. A microgrid can be allowed to operate islanded or interconnected with the main grid for local management of energy and resilience. Zhou *et al.* (2012) extended this discussion by considering autonomous voltage regulation in high-penetration PV applications. Their work indicated that sophisticated mechanisms have to be implemented in order to compensate for voltage and frequency fluctuations in such systems.

4.2 Fuzzy Logic in Energy Management

Fuzzy logic, introduced by Zadeh (1965), is a flexible way of dealing with imprecise data, and because of that, it is suitable for complex energy systems subjected to fluctuating inputs. Unlike binary logic systems, fuzzy logic operates on degrees of truth, thereby enabling nuanced decision-making capable of adjusting in real time to changes in both environmental and load conditions. Lin *et al.* (201) presented how fuzzy logic can be applied to the control of energy storage configurations in PV networks for output smoothening and, consequently, reducing grid dependency during peak periods of demand.

Zhou *et al.* developed an integrated autonomous voltage regulation model using fuzzy logic in 2012, which realised significant improvements in the management of high-penetration PV systems. In that process, the system is dynamically adjusted to fluctuating supplies of power through fuzzy logic, therefore maintaining the voltage stability and reducing the system stress. Along the same vein, Asano *et al.* (1996) made it known that with a fuzzy logic-based control system, energy use can be optimised: allowances are created to change grid load requirements and storage needs, leading to higher efficiency and a good level of load balance.

4.3 Advantages of Fuzzy Logic Controllers in PV Systems

In fact, studies have shown that FLCs work to enhance reliability and efficiency in the case of PV systems connected to the grid. Alam *et al.* (2014) presented a fuzzy logic-based ramp-rate control to mitigate solar PV fluctuations due to cloud cover. Their results showed that a fuzzy controller was overall successful in reducing voltage sags and power disturbances, particularly during partial cloud cover. In addition, Baran *et al.* (2012) also studied the application of FLCs in a distribution network with high PV penetration. In this system, fuzzy logic contributed much to enhanced stability due to dynamic adjustments for changeable load demand and energy availability.

In high-penetration PV systems, FLCs have also been observed to shift the dependency away from the grid through prioritised local energy sources such as PV and battery storage. This shifts the expense of energy, especially during peak pricing periods, and in the process, contributes to grid stability (Thomson & Infield, 2007). After identifying a gap between supply and demand, studies on load frequency control, such as Asano *et al.* (1996), note that FLCs can improve energy balance through the dynamic allocation of power from distributed sources depending on the prevailing conditions in real-time.

4.4 Conclusion of Literature Review

The literature demonstrates that fuzzy logic is extremely efficient in handling uncertainties associated with PV systems in high-penetration situations. Real-time control and adaptability strengthen the grid's stability, lower energy costs, and improve power quality through fuzzy logic usage. This paper builds upon existing research work involving a fuzzy logic-based control framework in grid-connected PV systems by maximising power utilisation between PV, battery, and grid sources under different environmental conditions. The discussed method will also address the crucial need for reliable energy management in renewable-integrated power systems.

5. Methodology

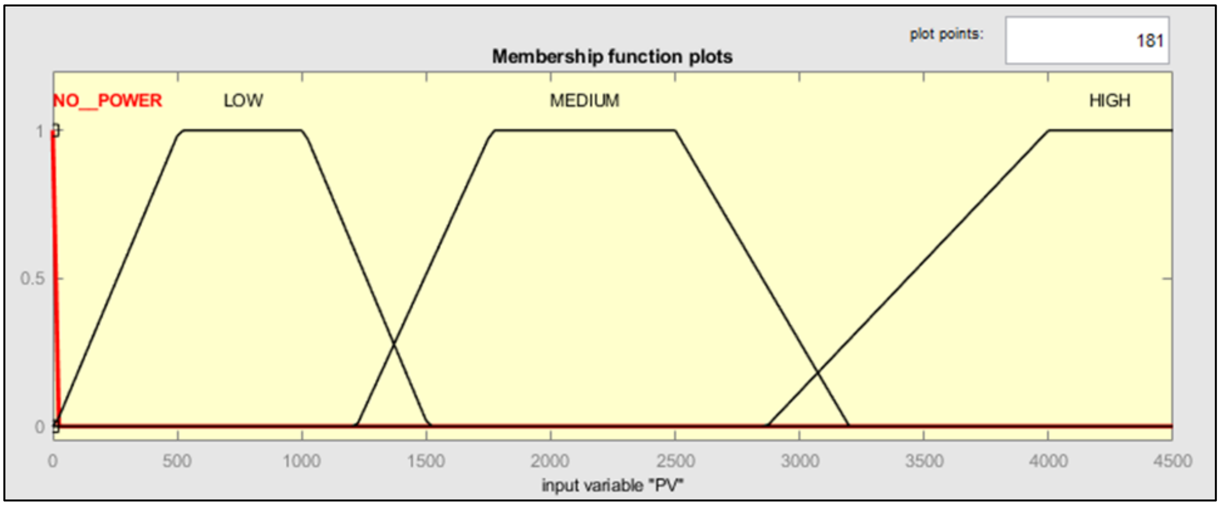
This research employed a fuzzy logic controller (FLC) that controls the power distribution of a grid-connected photovoltaic (PV) system with energy storage. The suggested FLC system will take into account real-time data from multiple input parameters, including PV power generation, grid availability, load demand, battery state of charge (SOC), and tariff rates, for its decision on the energy flow across PV, battery, and grid sources. The system performance was simulated using MATLAB Simulink to allow for various scenarios, including multiple load conditions and alterations in ambient conditions over 24 h.

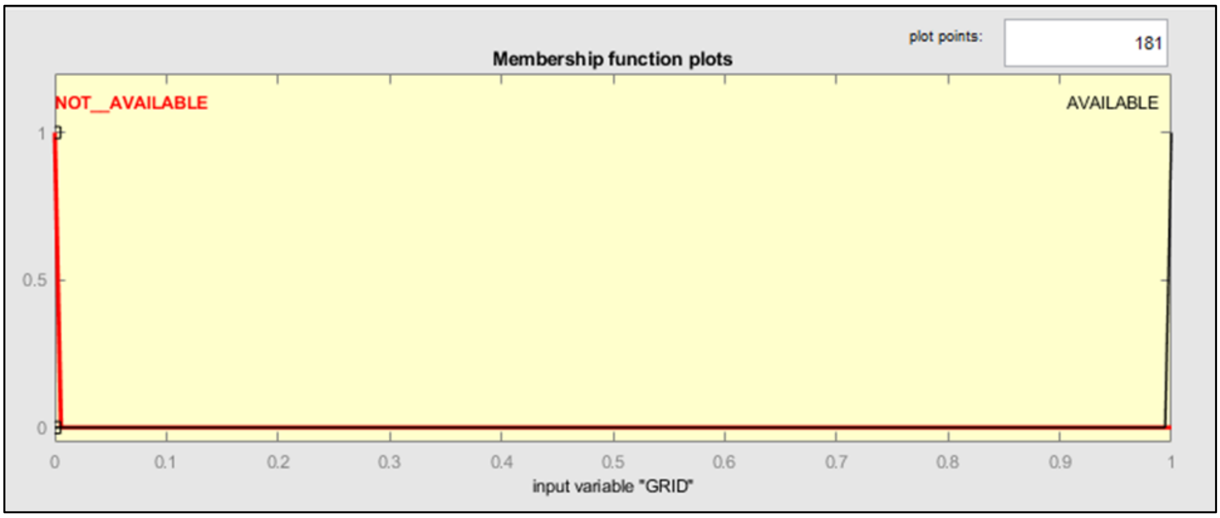
5.1 Fuzzy Logic Controller Design

It was tailored for the complexities of high-penetration PV systems, where the variability in solar power generation often created instability. Therefore, the selection of fuzzy logic was necessary because it handles uncertain or imprecise inputs and is effective at dynamically balancing power sources under variable conditions (Zadeh, 1965). The main five inputs to the FLC are:

1) **PV Output (PV)**: Represents real-time power output from the solar panels, categorised into membership functions: *No Power*, *Low*, *Medium*, and *High*.
2) **Grid Availability (Grid)**: Determines whether the main grid is accessible, with membership values of *Available* (1) and *Not Available* (0).
3) **Load Demand (Load)**: Measures the power requirement, with categories defined as *Very Small*, *Small*, *Medium*, and *High*.
4) **Battery State of Charge (SOC)**: Reflects the battery's charge level, ranging from *Low* to *Full*.
5) **Tariff Rate (Tariff)**: Captures the cost of grid energy, with membership functions for *Low* and *High* tariff periods.

Each input parameter is first associated with a membership function via a fuzzification process. The membership functions of the inputs, as can be observed in Figure 1, classify each parameter under normal conditions under which the PV systems operate.

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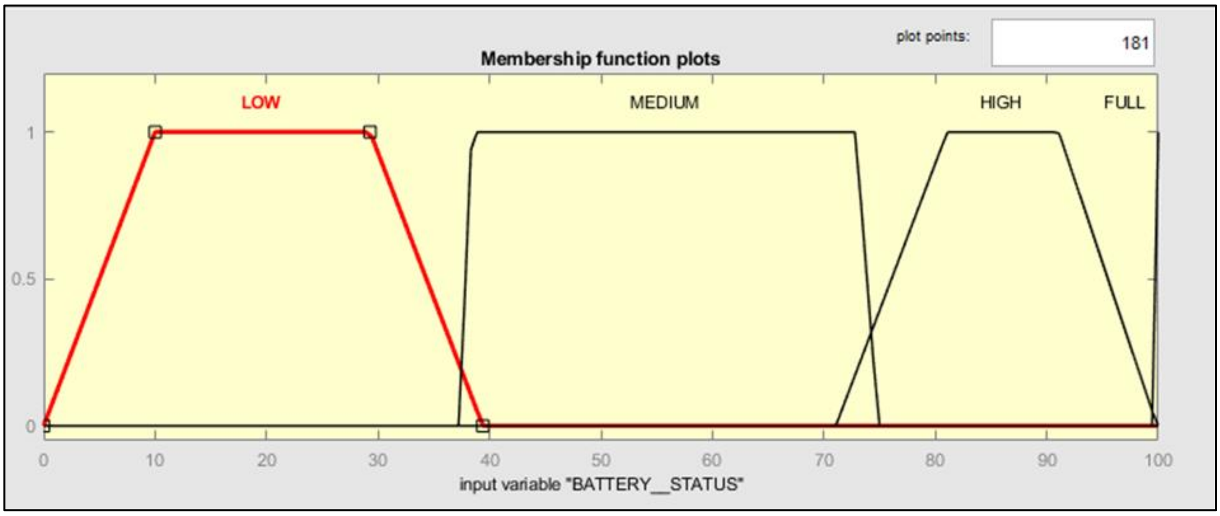
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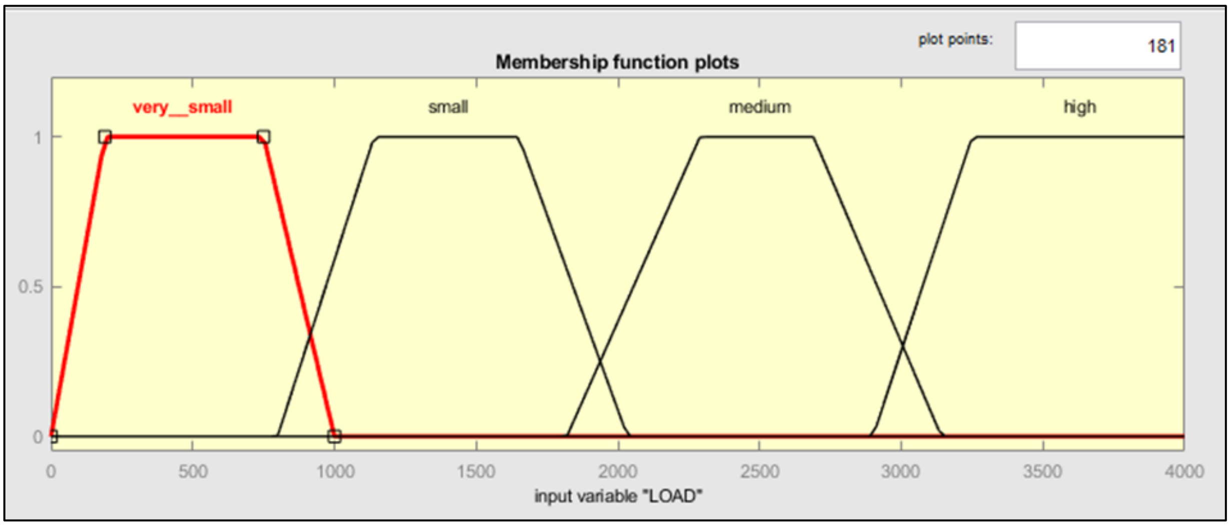
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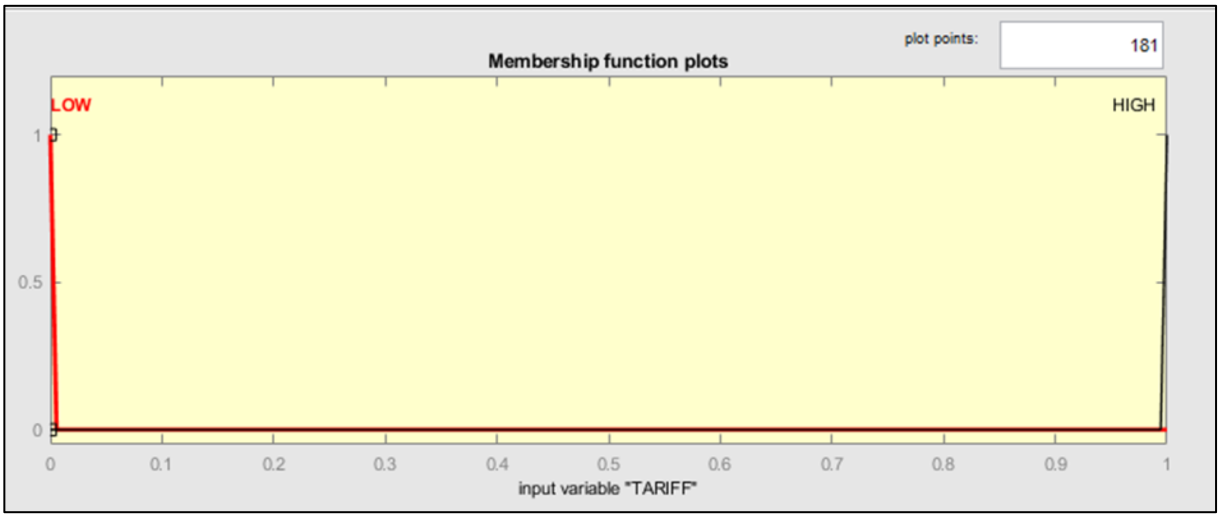

Figure 1: Member-ship Functions of a) PV, b) Grid, c) Battery status, d) Load, e) Tariff

5.2 Rule-Based Control Strategy

FLC is based on a set of "If-Then" rules that, through a continuous change in input conditions, enable real-time control of energy flow. These rules are put together to balance all the power sources: first priority is given to PV energy, battery usage, and grid power during peak tariff conditions. For instance, a high PV output with fullSOC in a battery would switch the system to PV for the load with minimum dependence on the grid. On the contrary, when PV output is low, and grid availability is low, FLC could increase the battery discharge to maintain stability.

It follows a 24-hour scheduling approach whereby specific rules are allocated to every hour in order to handle the foreseen variations in PV output and load demand. A detailed representation of a rule-based scheduler is shown in Figure 2, which identifies the conditions under which each energy source has priority depending on the five input parameters.

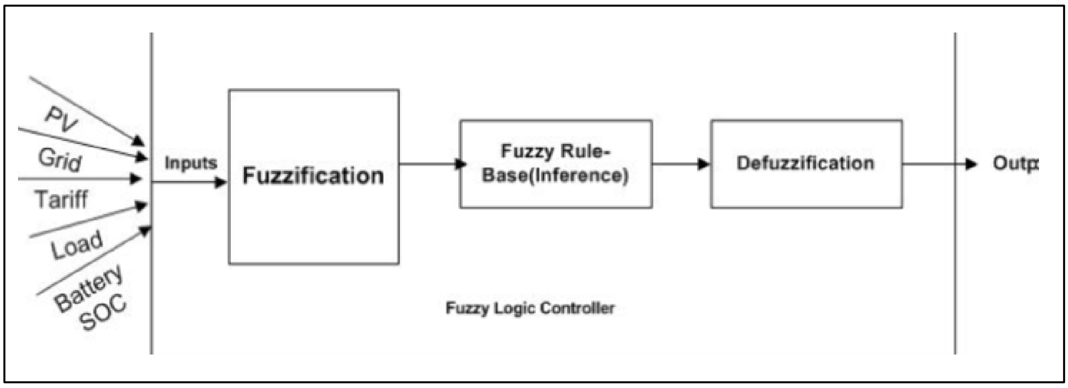

Figure 2: Fuzzy logic Controller for Grid-Connected PV system

5.3 Fuzzification, Inference, and Defuzzification

1) **Fuzzification**: Each input value is converted into fuzzy linguistic variables (e.g., *Low*, *Medium*) based on membership functions. For example, PV output ranges are categorized from *No Power* to *High* power based on real-time data and capacity.

2) **Inference**: The FLC uses a Mamdani inference system, where the rule base integrates fuzzy input values and applies "If-Then" rules to determine energy distribution across PV, battery, and grid sources. The MIN-MAX method is used for aggregation, combining fuzzy rules to yield intermediate results based on the degree of membership.
3) **Defuzzification**: The fuzzy outputs are converted back into precise control signals, using the centroid method to produce values that adjust energy flow between PV, grid, and battery sources. This ensures that the system operates within optimal parameters across various load and tariff conditions (Lin *et al.*, 2011).

5.4 Simulation Model and Case Scenarios

The proposed power management system based on fuzzy logic has been modelled and tested on MATLAB Simulink. The model tested the fuzzy logic controller over seven different case scenarios on a 24-hour timescale to deduce performance under variable PV output, grid availability, and load conditions.

The base scenarios are as follows:

- Case 1: No PV output; grid available; demand is high,
- Case 2: Moderate PV output; support from the grid, medium demand,
- Case 3: High PV output; low demand from the load,
- Cases 4-7: A series of combinations based on PV output, grid availability, and battery SOC levels (Table 1).

Table 1: Cases of the Simulink

Case	PV Power	Grid	BOS	Load	Tariff
Case 1	0 W	On	100%	4000 W	0
Case 2	2000 W	On	50%	2500 W	0
Case 3	4000 W	On	50%	2000 W	0
Case 4	0 W	On	100%	4000 W	0
Case 5	4000 W	Off	100%	4000 W	0
Case 6	0 W	Off	100%	4000 W	0
Case 7	2000 W	Off	100%	4000 W	0

The Simulink model (Figure 3) details the energy flow in the FLC and adjusts in real-time to changes in PV outflow and conditions on the grid. Results were evaluated based on how well the controller could keep voltages stable, prefer PV and battery power, and minimise grid power input during highly tariffed periods.

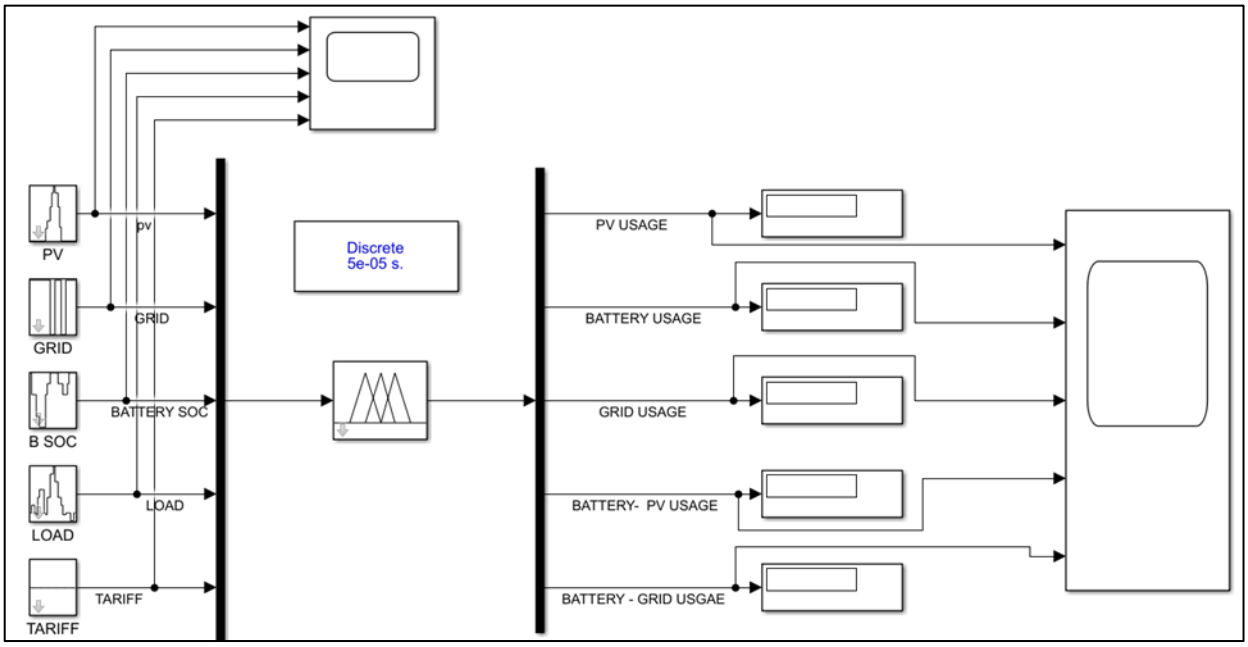

Figure 3: Simulink model of the proposed method

5.5 Evaluation Metrics

The performance of the FLC was assessed using the following metrics:

1) **Voltage Stability**: Monitored to ensure minimal fluctuation under different load conditions.
2) **Energy Source Utilization**: Analyzed to confirm the prioritisation of PV and battery sources.
3) **Grid Dependency**: Measured to evaluate grid reliance during high-tariff periods.
4) **Battery Discharge Time**: Calculated based on SOC and load requirements to avoid excessive depletion.

The simulation results demonstrate that the fuzzy logic-based controller effectively distributes energy from multiple sources, maintains grid stability, and reduces dependency on grid power during peak pricing hours.

6. Results

The performance of the FLC for flow control of power in a grid-connected PV system was tested for several simulations using MATLAB Simulink for a 24-hour period. Seven different scenarios have been simulated to test how the controller reacted under different conditions related to the PV output, the availability of the grid, the SOC of the battery, and the load demand. The performance metrics included voltage stability, grid dependency, and battery usage. The obtained results really show how effective FLC is in maintaining grid stability, optimising power flow, and reducing dependency on grid power during high-tariff periods.

6.1 Case Scenarios and FLC Performance

The seven case scenarios were designed to depict different conditions and challenge the controller's response. Each of these case scenarios was combined with varied conditions relevant to PV output, grid availability, load demand, and battery SOC to conduct an appropriate test of adaptability. A number of results are demonstrated here for these cases, which show capability in dynamically switching between power sources and giving priority to the PV and battery power sources over grid power where feasible.

Case 1: Low PV Output, High Load Demand, Grid Available

When the contribution from the PV was minimal, and the grid was available, FLC ensured that load requests were drawn from the grid for battery reserve. In these situations, the controller maintained the stability of voltage, therefore confirming that fuzzy logic will maintain grid stability at any time there is a low contribution from PV systems.

Case 3: High PV Output, Low Load Demand, Grid Available

Under high PV output and low load, the FLC maximizes the use of PVs with reduced dependency on the grid. The excess energy from PV is utilized to charge the battery, maintaining the state of charge close to full capacity. This case depicts clearly how the controller optimizes the usage of PVs if available, which diminishes unnecessary reliance on the grid.

Case 5: High PV Output, Grid Unavailable, High Load Demand

The experiment involved a seamless balance between the PV output and battery discharge in meeting high load demands without access to the grid. During peak sunlight hours, the major share of the load was met by the PV energy, which was discharged from the battery when the output from PV was very poor. The performance of the controller in this regard underlined the capability of giving priority to local resources and showed how, using fuzzy logic, self-sustained energy distribution can be managed.

6.2 Overall System Performance and Energy Flow Management

Over the simulated time period of 24 hours, the FLC regulated the flow of energy in accordance with the state of the load and tariff by switching between three different power sources: PV, grid, and battery. As indicated in Table 4.2, the controller maintained the voltage within the required limits, besides minimising the reliance on the grid and ensuring that the PV and battery sources were utilised when the tariff was high.

a. Voltage Stability

In all scenarios, the FLC succeeded in maintaining voltage within an acceptable range. In other terms, this is robustness when a variable load and PV output condition prevail. The fluctuations in voltage remained negligible across high-demand periods to exhibit the capability of the FLC in energy distribution stabilisation even with fluctuating environmental conditions.

b. Energy Source Utilization

This is when PV utilisation was at its maximum during sunlight hours, and during low loads, excess energy from the PVs charged the battery. The discharge rate of the battery would be adjusted by the FLC in accordance with the SOC level and the demand during loading to preserve battery life while building up reserves in time for high-demand hours.

c. Reduction in Grid Dependency

In an instance when the peak tariff hours were applied, the controller reduced the consumption of energy from the grid to almost zero with the aid of PV and battery powers, showing demand at the load. This optimal use of internal resources also aligns with the FLC objective to decrease grid costs and support energy independence.

7. Summary of Simulation Results

The performance of the FLC for all the scenarios proves their capability to manage the grid-connected PV system. The dynamic allocation of energy done by the fuzzy logic controller between photovoltaic, grid, and energy storage effectively optimised power flow, reduced dependency on the grid during high-cost periods, and maintained system stability.

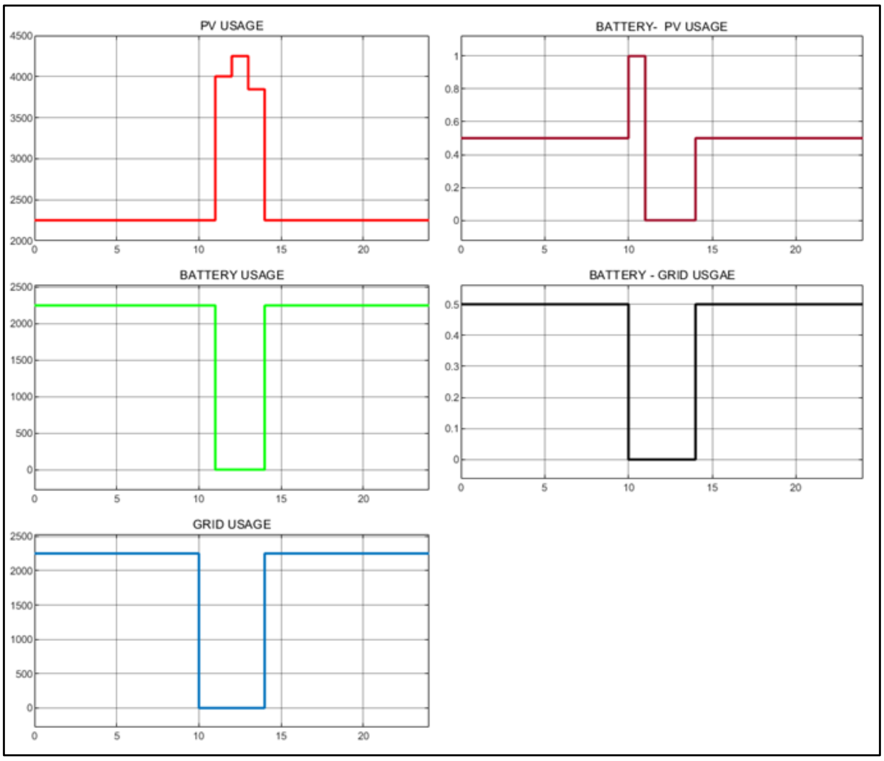

Figure 4.10: Result of the simulation

Figure 4 illustrates the results of the simulation for the period of 24 hours, where time-series data is available for PV output, grid usage, battery SOC, and load demand.

From the data of Thesis Hani 2, as observed, it is evident that the controller is capable of regulating power flow smoothly and keeping voltage stability under the alternating load demands and PV output.

7. Discussion

The results presented in this work validate the performance of the FLC for the management of power flow within a grid-connected PV system but, above all, when high-penetration PV scenarios are being dealt with. In particular, voltage stability and energy efficiency are considered. The section debates the results as related to implications on grid reliability, the benefits of fuzzy logic in energy systems, and areas for further research.

7.1 Fuzzy Logic in Managing High-Penetration PV Systems

The FLC contributed much to reduced grid dependency since there was a shift in the dependence on PV and batteries during the high tariff period. This confirms the work of Baran *et al.* (2012), who established that one of the strengths of FLCs is their adaptability in the management of distributed generation sources. Furthermore, the FLC dynamically readjusts energy distribution in response to real-time changes in load and environmental factors, hence avoiding some problems associated with high-penetration PV systems, which are voltage fluctuations and instability of the grid. In confirmation, Alam *et al.* (2014) proved that fuzzy logic can indeed result in improved quality power in systems whose renewable inputs are generally fluctuating.

In this regard, the voltage stability of the FLC operating under different load conditions is remarkable in that it shows that fuzzy logic is a very robust tool in intermittent PV generation. The result also agrees with that presented by Asano *et al.* (1996), who indicated that fuzzy controls bear great potential for responding to challenges in load frequency controls towards renewable dominant grids. Voltage stability, even when the controller operates under conditions of high load and low PV, further justifies the suitability of FLCs in balancing load demands against power availability.

7.2 Optimising Local Resources and Reducing Grid Dependency

One of the key successes recorded in this study for the FLC was in the reduction it achieved in grid reliance, especially at peak tariff hours. As observed in this paper, the controller ensures that battery discharge and PV output are prioritised during hours of peak demand. This, in turn, brings about a significant reduction in energy costs from the grid. This goes in line with the finding of Zhou *et al.* (2012), where fuzzy logic was a good tool in performing autonomous voltage regulation-cost minimisation in high-penetration PV systems. The application of FLC to prioritise local resources provides a unique characteristic, which enables the strategies to maximise self-sufficiency, reduce transmission losses, and also provide resilience to microgrid systems, as identified by Mitra, Heydt, and Vittal (2012).

7.3 Addressing Limitations of Conventional Control Systems

The flexible rule-based approach of the FLC offers a solution to limitations found in conventional control systems; these are usually based on rigid parameters and are insensitive, or less sensitive, to real-time environmental variations. The fuzzy logic system, in contrast to traditional controllers based on binary logic, was able to manage values that were not strictly 0 or 1 and to continuously update energy flow in response to shifting PV output and load demands quality, as noted by Zadeh 1965 in his original paper on fuzzy sets. This partial membership and the graduate energy flow, instead of their abrupt changes, helped the FLC avoid sudden jerks in power usage, as could have been expected from a binary logic system, and contributed to a smoother operation of the grid.

7.4 Implications for Grid Stability and Energy Policy

The most important contribution of the study is underlining the utilisation of fuzzy logic controllers to increase grid stability further on the integration of renewable energy sources. For highly penetrated PV regions, it may be possible for the wide adoption of FLCs to realise more stabilised voltage profiles, optimally utilised energy resources, and reduced reliance on grid power. The added advantages are that such benefits support energy policies for self-sustaining renewable systems; FLCs help meet demand more efficiently, thus reducing further investments in additional infrastructure.

7.5 Limitations and Future Research

Although the FLC showed promising performance in managing energy flow in several considered scenarios, a few limitations still remain. In this simulation model, ideal conditions have been assumed, and no major seasonal or weather-based variation in solar output has been considered; therefore, further studies will enhance this model with detailed weather data, including consideration of the influence of cloud cover and extreme changes in temperature on the performance of the FLC. Where this research was focused on a grid-connected PV system, further studies can be conducted using the FLC on hybrid systems that unite either wind or fuel cell sources of power.

Future research also needs to be carried out on the optimisation of the FLC rules for a particular microgrid setup, given that rule-based configurations can differ based on application type- residential or industrial- depending on several unique energy requirements. Further development in machine learning could push the performance of FLC even higher by carrying out adaptive rule optimisation based on historical energy usage and environmental data, potentially increasing the efficiency of this controller in the real world.

8. Conclusion

This work showed that FLC implemented power management in grid-connected photovoltaic systems. The simulations done with MATLAB Simulink were based on seven different scenarios in a 24-hour period and confirmed that the proposed FLC maintains voltage stability while optimising the operation of PV generation, battery storage, and grid power. It proved very efficient in reducing dependencies on the grid, particularly during high-tariff periods, by intelligently prioritising PV and battery sources.

The results obtained clearly bring out the major advantages of fuzzy logic over conventional binary control systems in handling the intrinsic uncertainties of renewable energy integration. As will be seen, the capabilities of the controller to make real-time adjustments based on multiple input parameters such as PV output, grid availability, load demand, battery state of charge, and tariff rates show its strength in managing high-penetration PV scenarios. These adaptive approaches go a long way in overcoming some of the major challenges related to voltage instability and power fluctuations created by renewable energy integration.

While the working module shows promising results, future research should focus on the incorporation of more detailed weather data and seasonal variations to enhance the controller's real-world applicability. Further, to enhance the versatility of FLC, its framework should be extended to hybrid systems that include wind or fuel-cell sources. This fuzzy-logic-based approach demonstrates, on the one hand, a landmark toward integral stability and efficient cost-effectiveness in integrating renewable energy sources into the existing grid to facilitate such a paradigm shift toward sustainable energy systems.

Conflict of Interest Statement

The authors declare no conflicts of interest.

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