

Energy Management and Control of Hybrid AC/DC Microgrid Using Fuzzy Logic Controller

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ABSTRACT

In a microgrid system, an energy management system is necessary to control the flow of power and energy between sources and loads and to provide high quality, safe, sustainable, and environment-friendly energy to consumers. It is a hybrid electrical system, low or medium-voltage, that includes small energy sources based on renewable resources as primary resources to provide high-quality electricity for small consumers, mostly operated in rural areas that are separated or isolated. To ensure the efficient Power Management and control, this article proposes an efficient Hybrid DC/AC microgrid using four renewable energy sources such as solar, wind, Biomass Generator and Lithium-ion batteries were chosen as storage system. The existence of both AC and DC microgrids has led to a new concept of hybrid AC/DC microgrids tied by an Interlinking Converter (ILC). It comprises a DC grid and AC grid interlinked by a bidirectional DC/AC converter. In addition, to provide higher voltages, the Multi-Input Booster (MIB) DC-DC converters are used as a power converter in between load and source to enforce and increase the PV depending on the voltage output signal. Further extract maximum power from the solar PV system, perturb and observe algorithm-based power point tracking control mechanism is proposed DC link voltage of ILC is regulated usually by DC side control in load sharing among sources in the DC microgrid. Adding up, to overcome the load fluctuation problem in a microgrid, this article introduced a Mamdani type 2 PID-fuzzy controller. Simulation Results reveal that the proposed type-II fuzzy PID controller can balance the power generation and demand properly and control both system frequency and tie-line power effectively

Keywords: Microgrid, Photovoltaic, Battery, Wind, Interlinking Converter, Multi-Input Booster, Mamdani type 2 PID-fuzzy controller.

INTRODUCTION

Microgrids are becoming increasingly important as our society moves towards a more sustainable and decentralized energy system. Here are a few reasons why microgrids are important:

- **Resilience and reliability:** Microgrids provide a localized source of power that can operate independently of the larger utility grid. This means that during power outages or other emergencies, microgrids can continue to supply power to critical facilities such as hospitals, emergency response centers, and water treatment plants.
- **Energy security:** Microgrids can reduce our reliance on fossil fuels and provide a more secure and stable source of energy. By integrating renewable energy sources such as solar, wind, and geothermal power, microgrids can provide a reliable source of power that is not subject to the volatility of fossil fuel markets.
- **Climate change mitigation:** By reducing our reliance on fossil fuels and integrating renewable energy sources, microgrids can help mitigate the impacts of climate change. Microgrids that incorporate energy storage systems can also help reduce the need for new fossil fuel-fired Peaker plants, which are typically used to meet peak demand.

- Cost savings: Microgrids can help reduce energy costs by avoiding peak demand charges and reducing reliance on expensive utility electricity during high-demand periods. They can also help reduce transmission and distribution costs by reducing the need for new infrastructure.
- Innovation and technological advancement: Microgrids are driving innovation and technological advancement in the energy sector. By integrating renewable energy sources, energy storage systems, and advanced control systems, microgrids are paving the way for a more sustainable and decentralized energy future.

In general, Microgrids are difficult to operate and design a hybrid system with all of the renewable and non-RES sources, storage devices, converters, and loads. The hybrid system's DC components are the wind turbine, solar panels, and battery bank, while the AC components are the diesel generator and load etc. The conversion of AC to DC and vice versa is handled using an IGBT-based high-power converter [1]. Constant power loads (CPLs) in DC MGs diminish the DC-DC converter's effective damping and may have destabilizing effects since CPLs have nonlinear dynamics and negative incremental impedance [2-3].

An MG can be either DC or a hybrid of DC and AC. Hence a DC microgrid is the best option in RES, power converters, and modern loads all require DC electricity to operate. To control MG in the past, PI/PID linear control, SMC, and artificial intelligence-based control were all used. Nonetheless, in the last decade, intelligent control of nonlinear systems has gotten a lot of attention [4]. As a result, common controllers such as neural networks, and fuzzy and neuro-fuzzy controllers have been researched. This paper discusses the controller framework for regulating voltage regulation in a microgrid with RES and an energy storage system. The self-tuning fuzzy proportional-integral-derivative (SFPID) controller was proposed in [5] which gives better performance in terms of overshoot, rising time, and settling time. As a result, a RES-based Fuzzy controller for loads input into the microgrid has been presented.

LITERATURE REVIEW

Overall, the literature on microgrids is vast and growing rapidly. Research in this area is focused on developing new design and control strategies, exploring the economic and environmental benefits of microgrids, and identifying best practices for microgrid implementation and operation. Here are some examples of literature reviews on microgrids, along with their references:

- "A review of microgrid design and control" by Rashedur M. Rahman and ManimaranGovindarasu, Renewable and Sustainable Energy Reviews, 2011. This review provides an overview of various design and control strategies for microgrids, including centralized and distributed control approaches.
- "Renewable energy integration in microgrids: A review of technologies, controls, and planning" by Mahdi Jamei and Reza Iravani, Renewable and Sustainable Energy Reviews, 2015. This review examines the integration of renewable energy sources, such as solar and wind power, into microgrids. It also discusses the role of energy storage systems in increasing the penetration of renewable energy.
- "Microgrid planning and operation: A review" by Wei Li and Rong Zeng, Renewable and Sustainable Energy Reviews, 2018. This review provides an overview of microgrid planning and operation, including capacity planning, energy management, and demand response. It also discusses the potential for microgrids to provide grid support services.
- "Economic analysis of microgrids: A review" by Ahmed M. Aboushady, Mohamed A. Ismail, and Ahmed F. Zobaa, Renewable and Sustainable Energy Reviews, 2016. This review examines the economic feasibility of microgrids, comparing the costs and benefits to traditional utility systems. It also discusses the impact of energy prices, regulatory frameworks, and government incentives on microgrid economics.
- "Microgrid implementation: A review of technical, economic, and social aspects" by BurakGulez and Suleyman Ersan, Renewable and Sustainable Energy Reviews, 2018. This review provides case studies of microgrid implementation in various settings, including universities, military bases, and remote communities. It also discusses the technical, economic, and social aspects of microgrid implementation.

- "Fuzzy Type-2 Mamdani Controllers for Power Systems: A Review" by A. S. Aneke, K. C. Ugwu and E. C. Nwafor, Energies, 2021. This review provides a review of recent literature on the application of T2MFLCs in power systems. The review covers various aspects of T2MFLCs in power systems, including their design, optimization, and performance evaluation.
- "Energy management-based hybrid fuel cell/battery for electric vehicle using type 2 fuzzy logic controller" by Younes, D., Boudiaf, M., & Karim, N., International Journal of Advanced Studies in Computers, Science and Engineering, 12(1),2023. This review provides Type-2 fuzzy controller is implemented and evaluated in the onboard hybrid power system simulation model. The results show that the management algorithm can improve its intervention during cycle change and power system efficiency by decreasing variance in battery state of charge.

Overall, these reviews demonstrate the diverse range of research topics related to microgrids, including design and control, renewable energy integration, planning and operation, economic analysis, and case studies of implementation.

PROPOSED METHODOLOGY: MICROGRID COMPONENTS

The objective of smart power systems is to combine all renewable energy sources to increase the electricity supply of clean energy sources. Microgrids provide a new infrastructure for more efficient, resilient and cost-effective power systems. The proposed methodology seeks a model for minimizing the Energy Cost (EC) and enhancing the power supply for rural areas by designing and analyzing four different hybrid system configurations based on integrating a biomass system with a photovoltaic (PV), wind turbine (WT) and battery system.

This research proposes the power management of hybrid DC/AC MG with the efficient use of RERs. Figure 1 illustrates the block diagram of the proposed work

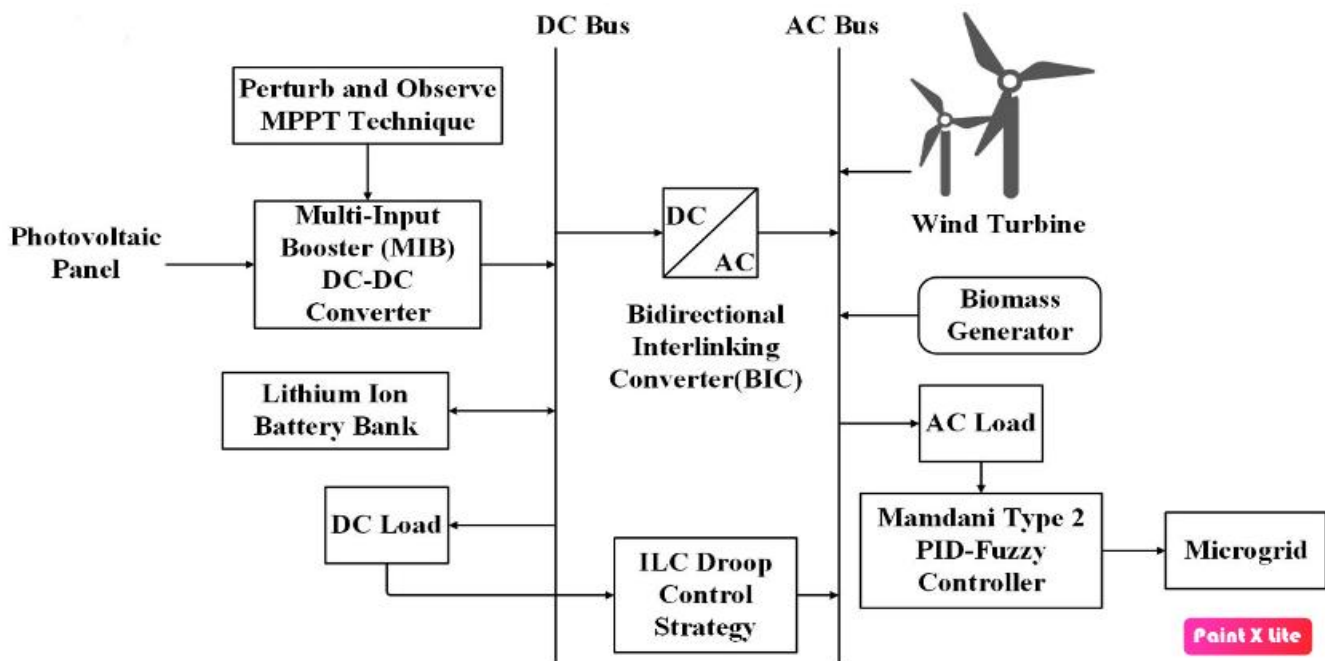


Figure 1: Block Diagram of the Hybrid Microgrid

The research proposed the energy-efficient hybrid RES (solar, wind, biomass and battery) for power management in a microgrid. Power electronic converters are utilized to connect these sources to the supply network through a common grid bus. Consequently, the study employs the DC/AC microgrid grids tied by an Interlinking Converter (ILC). Mamdani type 2 PID-fuzzy controller into the high-type control system, is proposed to overcome load fluctuations of the microgrid. This attains high performance and desirable responses for different scenarios of change in load. The proposed system is implemented in MATLAB/Simulink to verify the effectiveness of this control strategy. The procedure for the operating

strategy can be summarized in the following steps. Case study site selection was guided by the availability of solar energy and biomass resources which can be used in building the hybrid off-grid system. Microgrids have become an attractive option for distributed generation (DG) with the increase in Renewable Energy Sources (RES) and storage systems. Microgrids (MGs) are designed with the help of effective power extracted from renewable sources such as solar, wind, battery, and biomass.

Modelling of the Solar PV system

Weibull PDF is used to characterise the stochastic behaviour of the solar irradiance as it provided a good fit for the irradiance data of the chosen site compared to beta, gamma, lognormal and generalized extreme value distribution (GEV) PDFs. At any timeframe ‘ t ’, the Weibull distribution for the solar irradiance $s \text{ (w/m}^2\text{)}$ is given by Equation (1), and the shape parameter k' and the scale factor (c') are calculated at the time frame ‘ t ’ using the maximum likelihood estimation (MLE) method.

$$f(G) = (k/c) * (G/c)^{(k-1)} * e^{-(G/c)^k} \quad (1)$$

Where G represents the stochastic solar irradiance value, k is the dimensionless shape parameter, and c is the scale factor calculated using the maximum likelihood estimation (MLE) method

To analyse the solar PV output power, the continuous PDF is divided into different states for a particular time frame. Solar irradiance will be within limits in each state, the probabilities of all possible states for that particular hour are obtained, and these probabilities are used to obtain power generation in the time segment. The average power output of the solar PV array for a particular time frame ‘ t ’ or hour is given by

$$P_{pv}(t) = \sum_{st=1}^{N_s} P_{pv} \times P_s(s_{st}^t) \quad (2)$$

For a given state, during any particular time frame or any particular hour, the solar irradiance probability is given by

$$P_s(s_{st}^t) = \begin{cases} \int_0^{(s_{st}^t + s_{st+1}^t)/2} f(s_t) ds & \text{for } st = 1 \\ \int_{(s_{st-1}^t + s_{st}^t)/2}^{(s_{st}^t + s_{st+1}^t)/2} f(s_t) ds & \text{for } st = 2 \dots (N_s - 1) \\ \int_{(s_{st-1}^t + s_{st}^t)/2}^{\infty} f(s_t) ds & \text{for } st = N_s \end{cases} \quad (3)$$

If the power generated by the PV array with the average solar irradiance (i.e. if a state represents solar irradiance (w/m^2) is lying between 0 to 100, then the average (s_{st}^t will be $50 \text{ (w/m}^2\text{)}$) for st -th the state is calculated as.

$$P_{pv} = N_{pv} \cdot f_{pv} \cdot \eta_{mppt} \cdot ff \cdot I_{sc}(st) \cdot V_{oc}(st)$$

$$ff = (V_{oc} \cdot I_{sc}) / (V_{stc} \cdot I_{stc}) \quad (4)$$

Modelling of the Wind Energy System

Weibull PDF is suited to express the wind speed stochastic behaviour, as it provides a good fit for the wind speed distribution at the chosen site. Weibull PDF for the wind speed $v \text{ (m/s)}$ for any time frame t can be expressed as

$$f(v_t) = \frac{k'}{c'} \cdot \left(\frac{v_t}{c'}\right)^{k'-1} \cdot \exp\left(-\left(\frac{v_t}{c'}\right)^{k'}\right) \quad \text{for } c' > 1; k' > 0 \quad (5)$$

The average output power of the wind turbine (WT) for a particular time frame t or a particular hour is given by

$$P_{wt}(t) = \sum_{st=1}^{N_s} P_{wt_{st}} \times P_v(v_{st}^t) \quad (6)$$

The power generation of the WT depends on the velocity of the wind at that particular time. Therefore, the power generated by WT at the average wind speed v_{st}^t for any state st is determined as

$$P_{wt_{st}} = \begin{cases} P_{rw} \cdot N_w \cdot \left(\frac{v_{st}^t - v_{ci}}{v_r - v_{ci}} \right)^3 & \text{for } v_{ci} < v_{st}^t < v_r \\ P_{rw} \cdot N_w & \text{for } v_r < v_{st}^t < v_{co} \\ 0 & \text{else} \end{cases} \quad (7)$$

Modelling of Biomass Gasifier

Thermochemical conversion technology is used to convert biomass into clean and cool gas by partial combustion under a restricted air supply. This produced gas is used as an input for the fuel engine to generate electricity. In this study, a 10 kW rated biomass gasifier is considered, which is operated for 12 h per day during the peak load. The total annual biomass energy generated is given by Equation (8):

$$E_b = N_b \times P_b \times t_w \quad (8)$$

The maximum rating of the gasifier depends on the total available biomass in a year, the calorific value of biomass and the efficiency of the biomass gasifier, which is given by

$$P_b^{\max} = \frac{\text{total} * 1000 * CV_{bm} * \eta_b}{365 * 860 * t_{bio}} \quad (9)$$

Modelling of Battery

In this study a battery energy storage system(BESS) is designed to supply the peak load demand for at least 30 min. Lithium Ion Cellare used as BESS because of their short response time, low self-discharge rate (3%–20%), high cycle efficiency (70%–85%), and low capital cost. Lithium-ion cells also require much tighter voltage tolerance on detecting full charge and once fully charged they do not allow or require to be trickle or float charged. It is particularly important to be able to detect the full charge state accurately because lithium-ion batteries do not tolerate overcharging. They over-heat and this reduces their life but in extreme circumstances, it can lead to them catching fire or even exploding. Most consumer-orientated lithium-ion batteries charge to a voltage of 4.5 volts per cell and this has a tolerance of around ± 50 mV per cell. To operate BESS reliably and efficiently, a complete study of battery requirements while charging and discharging, energy loss and efficiency is required. If the total energy generated from the PV, biomass, and wind is more than the energy demand, then the battery bank will charge, and whenever there is an energy deficit to meet the load, the energy stored in the battery will supply the deficit energy to the load.

Component Network	Parameter Description	Operational Target Value
Solar Photovoltaic	Rated Array Power / Nominal DC Output	10 kW / 400 V
Wind Energy System	Turbine Generator Capacity / Nominal AC Bus	15 kW / 415 V (RMS)
Biomass Gasifier	Rated Plant Output Generation Capacity	10 kW
Lithium-Ion Battery	Storage Capacity / Nominal Bus Link Voltage	48 V / 800 V DC
Interlinking Converter	Switching Filtering Inductance ($(L_{\{f\}})$, $(R_{\{f\}})$)	24 mH, 0.9 Ω
Control System	PWM Switching Frequency / Sampling Time Step	8 kHz / 0.3 ms

Table 1: Nominal Hybrid Microgrid System Parameters

Griid -Tied Operation

Grid-connected mode is further classified into two types based on the contract. i) Non-dispatched power: In this mode, DGs operate in MPP, and excess power generated after meeting local loads is fed to the grid ii) Dispatched power mode: In this mode, DC bus voltage is regulated in two ways a) Interlinking converter (ILC) is controlled to regulate DC link voltage, and DG units on AC bus and DC bus are harmonized for supplying dispatched power with power balancing. DC-DC converter runs PV and wind generators at maximum power point in normal mode or power flow control mode, charging the battery from the grid and discharging when power generated by PV and wind is less than demanded power from the grid. DGs connected to the AC bus and interlinking converter are operating in power flow control mode, and DGs connected to the DC bus are responsible for DC link voltage regulation. Power-driven into to grid can be controlled by changing the phase angle and magnitude of the fundamental voltage of the inverter for the grid. The existence of both AC and DC microgrids has led to a new concept of hybrid AC/DC microgrids which consists of both AC and DC grids tied by an Interlinking Converter (ILC). It comprises a DC grid and AC grid interlinked by a bidirectional DC/AC converter. Such a hybrid AC/DC microgrid has the advantages of both AC and DC with increased efficiency and less cost. The DC comprises a PV panel system and a battery bank storage system. The DC loads are connected to the DC via the DC bus. The AC comprises the wind turbine (WT) system and Biomass.

Bidirectional DC/AC Converter

The bidirectional DC/AC converter is an online converter which is common between the DC bus and the AC bus. It allows the bidirectional flow of power between DC bus and AC bus. It can work both as an inverter and as a rectifier. When there is a power deficit in the DC MG, the converter works as a rectifier and power are supplied from the AC side to the DC MG, thereby preventing the isolation of the loads connected to the DC bus. The voltage source control technique is used which has precise control over the magnitude, phase, and frequency of the voltage. The bypass diodes which are antiparallel to the switches help in the circulation of reactive power and the flow of active power in both directions. The sinusoidal pulse width modulation technique is used as the switching scheme.

An important feature of grid-connected DC microgrids or DC distribution systems is the ability to inject or suck power from the grid based on the generation and loading conditions. To do that, a controlled AC-DC/DC-AC converter that allows bi-directional power flow has been designed. This controlled converter is responsible for controlling the amount of power flowing between the AC and the DC grids. Power flow from the AC to the DC grid is very important to cover any deficiency in the demand in the DC grid due to normal or pulse loading. Moreover, Power flow from the DC to AC grid is needed when there is an excess in power from renewable energy sources on the DC bus.

The current on the DC side is assumed positive if flowing from the Ac grid to the DC system and vice versa. Hence, if i_{dc}^{ref} is set to a positive value, the bi-directional AC-DC/DC-AC converter will autonomously operate in the rectifier mode and the modulating signals will be lagging the grid voltage. However, if it is set to a negative value the modulating signals will be leading and the DC network will inject current to the AC grid. In both modes of operation, the vector decoupling technique used allows unity power factor operation by setting i_d^{ref} , which is responsible for the reactive power, to zero. The fully controlled bi-directional converter is operated at an 8 kHz switching frequency and sampling time of 0.3 ms, which allows the controller to detect and respond quickly to different load demands at either the AC or DC sides. The converter is designed to operate at a low THD and unity power factor. A 24 mH inductor with 0.9-ohm losses is connected between the AC grid and the converter to filter harmonics associated with the fundamental current waveform.

DC-DC Converter

Only certain solar panels mostly in the sector are 12 or 24V (2 to 5A), however, the load requirements involve higher voltages, requiring the use of a boost converter. DC-DC converters are being used as a power converter in between load and source to enforce and increase the PV depending on the voltage output signal. Further, the work is focused to build a new boost converter of Multi-Input Booster (MIB) converter for high gain system

and its equivalent system with a perturb and observing algorithm-based maximum power point tracking control mechanism to extract maximum power from the solar PV system. This Multi-Input DC-DC converter improves DC side load sharing and DC bus voltage regulation of ILC along with battery SOC control of individual DC-DC converters in the DC microgrid (DCMG). DC link voltage of ILC is regulated usually by DC side control in load sharing among sources in the DC microgrid. AC microgrids are based on the ILC droop control coefficients of sources on either side and transfer power from DC microgrid to AC microgrid and vice-versa. Additionally, the ILC control prevents any negative sequence currents from entering the AC source.

Multi-Input Booster (MIB) DC-DC Converters

Only certain solar panels mostly in the sector are 12 or 24V (2 to 5 A), however, the load requirements involve higher voltages, requiring the use of a boost converter. Multi-Input Booster (MIB) DC-DC converters are being used as a power converter in between load and source to enforce and increase the PV depending on the voltage output signal. The multi-input converter is a circuit structure that integrates different input voltage sources with different voltage levels and supplies an output dc load.

ILC Droop Control Coefficient

To address these shortcomings, this paper proposes a novel, generalized droop scheme of ILC for autonomous power-sharing and control of a hybrid microgrid. A standalone hybrid microgrid is considered where the control of active power is more complex as compared to the grid-connected mode. The ac microgrid operates on frequency droop while voltage droop is used in the dc microgrid. A 3-dimensional plane is proposed for ILC control where the axis corresponds to dc voltage, ac frequency and converter power. The converter utilizes frequency droop at the ac terminal and voltage droop at the dc terminal so any change in dc voltage or ac frequency results in active power flow from an underloaded to the overloaded grid. The three quantities, namely active power, ac frequency and dc voltage, are introduced in the outer control loop of the converter along with three scaling factors which define the converter frequency and voltage droop.

To enable autonomous power-sharing between ac and dc grids, dc voltage droop and ac frequency droop are implemented in the outer control loop of the converter. Any load change in the ac grid will result in frequency variation and the power flow through the converter will change according to the frequency droop. Similarly, any dc load change will result in voltage variation which will change the converter power according to the dc voltage droop.

Controller System

The voltage and frequency of MGs are strongly impressionable from the active and reactive load fluctuations. A change in load leads to an imbalance between generation and consumption. The output voltage and frequency of the DGs are primarily controlled by the droop characteristics. But, in case of severe changes in load, the DGs may be failed and the Microgrid is collapsed. Subsequently, the research proposed the intelligent Mamdani type 2 PID-fuzzy controller into the high-type control system, which exhibits high performance and desirable response for different scenarios of change in load.

AC/DC Loads

AC and DC loads were placed at the terminal of the DC bus and AC bus as shown in Figure 1. both AC and DC power goes through a smart distribution system and intelligent power tap, which are able to measure the power flow i.e function of BIC and ILC DCS. The AC loads consist of an air conditioner, TV, lighting, refrigerator having a choice of operating under design of 2KW and DC load consist of an EV charger (2 KW).

All the power converters (DC-DC converters for generating units, a bidirectional DC-DC converter for the Li-ion battery, and an inverter for AC supply to loads) were developed for this study.

This article mainly drives with the components which are discussed this chapter, also design an unique proposed system with fuzzy logic-based controller for effectual power transactions.

PROPOSED METHODOLOGY: FUZZY LOGIC BASED MICROGRID CONTROLLER

Fuzzy logic control is mostly based on the rules made by the Linguistic variables. Unlike other methods, fuzzy logic control does not need to do complicated math. It only needs to do simple math to control the model. Even though it is based on basic math, it works well in a control system. Thus, this method is one of the best ways to control a plant and is more accessible than other ways.

Controlled by Fuzzy logic is based on the idea of Fuzzy sets. In fuzzy set theory, each element has a level of membership with which it is part of any given set. A fuzzy set is a type of set with a lot less clear boundary. The Fuzzy Logic Controller (FLC) is more commonly used when the precision required is low, and the plant does not need a lot of complex math. Even though it is based on basic math, it is still fascinating. it performs well in a control system. As a result, this strategy is one of the most influential and simple ways to regulate a plant. The fuzzy set theory underpins fuzzy logic control. Each element in fuzzy set theory has a degree of membership with which it belongs to any given set. Fuzzy sets are similar to classical sets but with significantly softer bounds. The Fuzzy Logic Controller (FLC) is more commonly employed when intermediate precision is required, and the plant does not require significant mathematical analysis. Other benefits include [6]:

- It does not necessitate extremely accurate inputs.
- An efficient reaction does not necessitate the use of fast microprocessors.
- It only requires a small amount of data, namely rules and membership functions.
- It's more efficient and can handle nonlinear models better.

A fuzzy action is also occurred between the grades of type-II membership functions due to which it can enhance the fuzziness and simultaneously imprecise data and is controlled in a precise manner. Figure 2 depicts the entire process incurred with the type-II fuzzy system. Mamdani 2FLC. This explained that there are five interconnected blocks in this figure, i.e., fuzzifier, rules, inference, type reducer and defuzzifier. A mapping exists between crisp inputs to crisp outputs of the IT2FLS and is expressed as $y=f(x)$. The fuzzifier converts crisp inputs X to an interval type-2 fuzzy set. The general configuration for both T1FLS and IT2FLS is the same, but the only difference is that the antecedents and consequents of IT2FLS are represented as type-2 fuzzy sets.

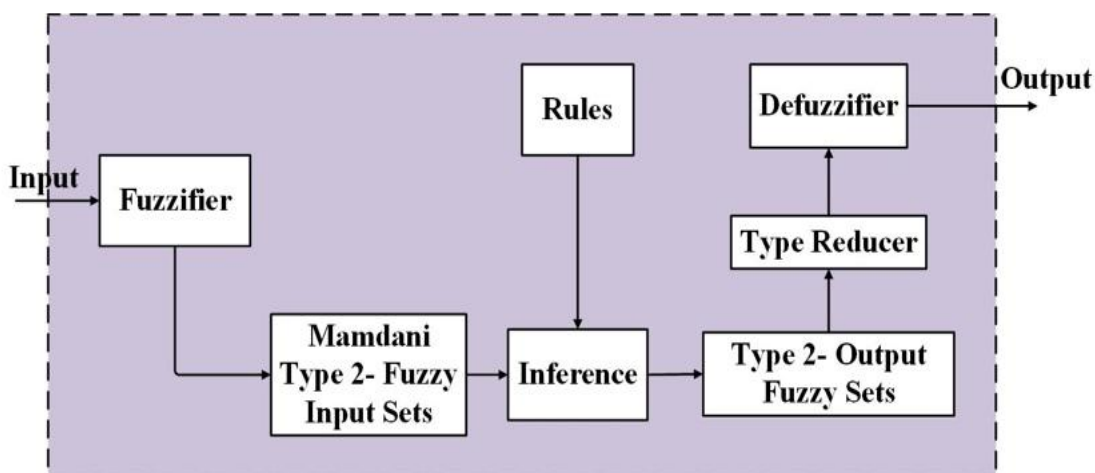


Figure 2: Block Diagram of Type II Fuzzy Controller

Rules are combined through an inference engine. It produces output type-2 fuzzy sets from input type-2 fuzzy sets. The type reducer reduces the type-2 fuzzy sets into a type-1 fuzzy set output. Through a defuzzifier, it is converted into crisp output. Crisp output can be applied to a particular plant which has to be controlled.

Design of Type-2 Fuzzy PID Controller

To describe details of the type-II fuzzy controller along with fuzzification and fuzzification it goes through different steps. In general, the fuzzy control rules of the discrete Mamdani controller [23], which has three inputs $e_1(k)$, $e_2(k)$, $e_3(k)$ and one output $u(k)$, will be written

$$R^{\theta}: \text{"IF" } e_1(k) \text{ "is" } E_1^{\theta} \text{ "AND" } e_2(k) \text{ "is" } E_2^{\theta} \text{ "AND" } e_3(k) \text{ "is" } E_3^{\theta} \text{ "THEN" } u(k) \text{ "is" } U^{\theta} \quad (10)$$

Where $\{R\}^{\theta}$ signifies the specific θ th rule configuration instance, E_1^{θ} , E_2^{θ} and E_3^{θ} represent the input interval Type-2 fuzzy sets mapping the monitored error metrics at time-step (k) , and U^{θ} defines the corresponding crisp output control consequence value

Using the ‘and’ function, the antecedent part of all rules is created. In this simulation, Mamdani fuzzy inference system has been applied. T1 Fuzzy sets showed limitations in the ability to model and minimize the effect of uncertainties.

That is because the T1 fuzzy set is certain in the meaning that its MF degrees are crisp values. On the other hand, the type-2 fuzzy sets were described by membership functions that are themselves fuzzy which attracted more attention. Since the scope of fuzzy control is very wide, various controller structures are possible, differing in the number of inputs and outputs, their fuzzy sets, membership functions, fuzzification method, a form of control rules, type of output mechanism and method of defuzzification. A Mamdani type of fuzzy engine is perceived, and the FLC output is calculated by using the defuzzification method of the Centre of gravity. The parameters K_1 and K_2 are scaling factors, and the gains of the PID are indicated with K_P , K_I , and K_D , and N represents the filter coefficient. Four types of inference schemes (including Mamdani’s) have been investigated by Ying, but a uniform equation for the composed fuzzy output was derived.

Simulation Results and Discussion

To obtain the above response the two-area transfer function model of interconnected MG system is developed in Simulink environment and necessary programs are written in .m file of MATLAB2021 software through 4GB ram, Intel Core i5 @ 3.5GHz processor-based system. The ac and dc sub-grids are modelled. For load frequency control, the system uncertainties are affected individually and finally in combined form to trace out different dynamic responses. the proposed PV-fed dc-bus charging station system and the corresponding control schemes are built-in MATLAB/Simulink. The nominal frequency of the ac grid is 50 Hz and the voltage of the dc microgrid is 800 V. The converter reference power is set at 10 kW which indicates the maximum power that can be delivered to the dc microgrid. The effect of coupling on the defined droop coefficients is also discussed in both scenarios with different load changes within the hybrid microgrid.

Case Study : Analysis with Different Load Conditions

This section of the proposed study deals with this must be changed to Type-1 (or conventional PID), as your study does not introduce or simulate a "Type III" fuzzy system under different uncertainties conditions of the MG system. Regarding this, the LFC study due to various uncertainties is demonstrated through different scenarios.

Variation of only load (ΔP_L): In this case study, the dynamic system simulation responses obtained during localized load step change events (ΔP_L) are illustrated in Figure 3. Quantitative evaluation indicates that under unperturbed nominal operating parameters, the conventional Type-1 FLC demonstrates shorter rise times, reduced settling delays, and smaller Integral of Absolute Error (IAE) accumulation values compared to the Type-2 layout. However, the Mamdani Type-2 Fuzzy structure exhibits superior tracking capabilities and parameter insensitivity when encountering unmodeled structural dynamics, stochastic distribution variations, or external measuring path noise injections, justifying its use in complex hybrid microgrid applications despite the higher computational latency induced by internal type-reduction routines.

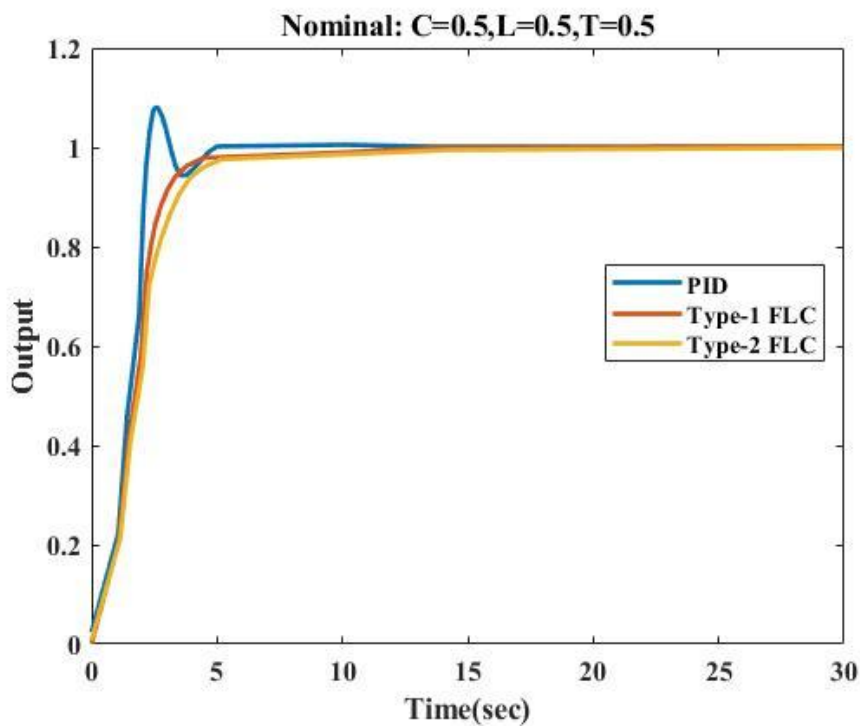


Figure 3. Dynamic Responses Obtained Via Fuzzy Controller

From figure 3, both the type-1 and type-2 fuzzy logic controllers outperform the conventional PID controller in terms of overshoot. The conventional PID controller performs better concerning rise-time and integral of absolute error (IAE). The type-1 FLC performs better than the type-2 FLC in terms of rise-time, settling-time, and IAE. Further, improve the fuzzy logic controller outputs using a Mamdani type FIS since it also provides lower MF scale and lag parameters for output membership functions. However, a Mamdani type-2 FLC introduces additional computational delay due to the expensive type-reduction process.

CONCLUSION

The hybrid AC/DC microgrid consists of both AC and DC grids tied by an Interlinking Converter (ILC). It comprises a DC grid and AC grid interlinked by a bidirectional DC/AC converter. Lithium-ion batteries were chosen for this study due to their high energy density, long life cycle, and high efficiency. Multi-Input Booster (MIB) DC-DC converters are being used as a power converter in between load and source to enforce and increase the PV depending on the voltage output signal. AC microgrids are based on the ILC droop control coefficients of sources to transfer power from DC microgrid to AC microgrid. The voltage and frequency of MGs are strongly impressionable from the active and reactive load fluctuations. Mamdani type 2 PID-fuzzy controller into the high-type control system, exhibits high performance and desirable response for different scenarios of change in load.

This research demonstrates that the fuzzy-PID controller configuration is a highly viable alternative for controlling power converters and non-linear systems within a hybrid grid layout. Quantitative simulation data from Figure 3 confirms that while a conventional PID or Type-1 FLC framework provides superior rise times and lower absolute error values under exact nominal conditions, the Type-2 membership setup offers exceptional uncertainty-mitigation capabilities. In further, it is possible to extend and observe controller efficiency with different case studies with only solar power variation and only Wind power variations and mixed up all the power sources variation simultaneously for satisfying high load demand conditions. This proposed control strategy successfully reduced the renewable fluctuations in the microgrid.

REFERENCES

1. Bouchekara, H.R.E.H., Javaid, M.S., Shaaban, Y.A., Shahriar, M.S., Ramli, M.A.M. and Latreche, Y., 2021. Decomposition based multiobjective evolutionary algorithm for PV/Wind/Diesel Hybrid

- Microgrid System design considering load uncertainty. *Energy Reports*, 7, pp.52-69.
2. Gamil, M.M., Senjyu, T., Masrur, H., Takahashi, H. and Lotfy, M.E., 2022. Controlled V2Gs and battery integration into residential microgrids: Economic and environmental impacts. *Energy Conversion and Management*, 253, p.115171.
3. Gui, Y., Han, R., Guerrero, J.M., Vasquez, J.C., Wei, B. and Kim, W., 2021. Large-Signal stability improvement of DC-DC converters in DC microgrid. *IEEE Transactions on Energy Conversion*, 36(3), pp.2534-2544.
4. Jabeur, R., Boujoudar, Y., Azeroual, M., Aljarbouh, A. and Ouaaline, N., 2022. Microgrid energy management system for smart home using multi-agent system. *International Journal of Electrical & Computer Engineering* (2088- 8708), 12(2).
5. Kaysal, A., Köroğlu, S. and Yüksel, O.Ğ.U.Z., Self-tuning Fuzzy PID Controller Design and Energy Management in DC Microgrid: Standalone and Grid Connected Mode. *Celal Bayar University Journal of Science*, 18(1), pp.41-51.
6. Jafari M, Malekjamshidi Z, Zhu J, Khooban M-H. A Novel Predictive Fuzzy Logic-Based Energy Management System for Grid-Connected and Off-Grid Operation of Residential Smart Microgrids. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2020;Jun;8(2):1391–404.
7. Fathy, A., Alanazi, T.M., Rezk, H. and Yousri, D., 2022. Optimal energy management of micro-grid using sparrow search algorithm. *Energy Reports*, 8, pp.758-773.
8. Dawood F, Shafiullah G, Anda M. Stand-Alone Microgrid with 100% Renewable Energy: A Case Study with Hybrid Solar PV-Battery-Hydrogen. *Sustainability*, 2020;Mar 6;12(5):2047.
9. Hu, J.; Shan, Y.; Guerrero, J.M.; Ioinovici, A.; Chan, K.W.; Rodriguez, J. Model predictive control of microgrids—An overview. *Renewable and Sustainable. Energy Rev.* 2021, 136, 110422.
10. Meng, L.; Sanseverino, E.R.; Luna, A.; Dragicevic, T.; Vasquez, J.C.; Guerrero, J.M. Microgrid supervisory controllers and energy management systems: A literature review. *Renew. Sustain. Energy Rev.* 2016, 60, 1263–1273.