RESEARCH PAPER

Hybrid Optimization and Intelligent Control Framework for Distributed Generation Using HOMER and Fuzzy Logic

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ABSTRACT
This study investigates the optimization of distributed generation (DG) systems through the combined use of HOMER software and Fuzzy Logic Control (FLC). HOMER provides a robust platform for simulating and optimizing both stand-alone and grid-connected DG configurations, evaluating their techno-economic feasibility based on local renewable resource availability. By modeling diverse generation technologies, HOMER supports sustainable energy planning and cost-effective system design. Building upon this, a fuzzy logic–based control strategy is proposed to intelligently manage power source selection and allocation within distributed networks. FLC offers an adaptive and computationally efficient means to address nonlinearities and uncertainties inherent in DG operation, thereby improving system reliability and performance. The DG framework considered integrates renewable energy sources (RES)—such as solar photovoltaic, wind, and fuel cells—with non-renewable energy sources (NRES), including fossil fuel and gas-based units. Given increasing environmental concerns, fossil fuel depletion, and rising energy costs, sustainable DG solutions are becoming critical. Nevertheless, integration challenges related to stability, safety, and power quality necessitate effective optimization and intelligent control mechanisms to ensure reliable and efficient distributed energy generation.

Keywords: *Distributed Generation; HOMER Software; Fuzzy Logic Control; Techno-Economic Optimization; Renewable Energy Systems; Hybrid Energy Systems, Intelligent Control; Sustainable Energy*

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I. INTRODUCTION

Renewable energy sources (RES), such as solar and wind energy, are clean, cost-effective, locally available, and virtually inexhaustible [1], [2]. These non-polluting and environmentally friendly resources have gained global attention as viable alternatives to conventional fossil-based generation, helping to address the escalating energy crisis and the need for sustainable power solutions [3]. This transition has driven a growing interest in distributed generation (DG) systems, leading to a significant increase in the number of small-scale generators integrated into distribution networks [4].

The ongoing shift toward decentralized and renewable-based power systems positions DG as a vital element of modern energy infrastructure [5]. However, the integration of multiple heterogeneous sources including solar photovoltaics, wind turbines, fuel cells, and fossil-fuel generators introduces complex challenges related to system stability, protection, reliability, and economic optimization. Conventional optimization methods often fall short in handling the nonlinearities, uncertainties, and dynamic characteristics inherent in hybrid DG systems [6].

The software HOMER (Hybrid Optimization Model for Electric Renewables) is extensively used for techno-economic analysis and system design of DG configurations, enabling evaluation of various energy combinations based on cost, performance, and resource availability [7]. Nevertheless, HOMER lacks real-time adaptability for intelligent control and source coordination. Fuzzy Logic Control (FLC), by contrast, offers a flexible, computationally efficient, and robust approach for managing nonlinear systems under uncertainty. Integrating FLC with HOMER-based optimization can therefore enhance decision-making in DG systems improving reliability, efficiency, and sustainability under variable load and environmental conditions [8-9].

Distributed generation also offers several key advantages, including reduced transmission losses, improved reliability, enhanced load management, and significant environmental benefits [10-12]. Yet, the integration of DG units within distribution networks raises concerns related to system protection, power quality, and operational stability, particularly under high penetration levels. These challenges highlight the urgent need for advanced control strategies that ensure consistent power delivery while maintaining quality and reliability standards [13-15].

Distributed generation provides multiple advantages, such as minimizing transmission losses, enhancing system reliability, improving load management, and contributing to environmental sustainability [10–12]. However, the integration of DG units into existing distribution networks also introduces challenges related to protection

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coordination, power quality, and overall operational stability—issues that become more pronounced at higher penetration levels. These concerns underscore the necessity for advanced control methodologies capable of ensuring stable, high-quality, and reliable power delivery under varying operating conditions [13–15].

This work proposes an optimized fuzzy-based control strategy for managing DG systems, where power source selection depends on two main factors: available capacity and proximity to the load centre. HOMER is employed to identify the most suitable renewable DG configurations for specific regional conditions. Given FLC's adaptability and ease of implementation, this approach presents an intelligent framework for efficient, reliable, and sustainable distributed energy management.

II. PROPOSED SYSTEM

Distributed generation (DG) networks integrate a diverse mix of energy sources, particularly renewable energy sources (RES) such as solar, wind, and geothermal power. Compared to conventional centralized systems, DG offers several advantages, including peak load reduction, energy cost stabilization, waste energy recovery, enhanced power quality and reliability, improved overall efficiency, and superior environmental performance [2]. Owing to these benefits, DG is anticipated to play an increasingly critical role in future power systems [3].

The proposed DG control framework developed in this study is illustrated in Figure 1. Three primary distributed sources—wind turbines, solar photovoltaic (PV) systems, and micro-turbines—are considered, though the approach can accommodate any number or combination of DG units [5]. The operation begins with metering centres that collect real-time data from both load and generation units. These measurements are transmitted to the Fuzzy Logic Controller (FLC), which evaluates the balance between available and required power. Based on this analysis, the FLC sends control signals to the switching centre, directing power flow from the most suitable source to meet demand efficiently and reliably.

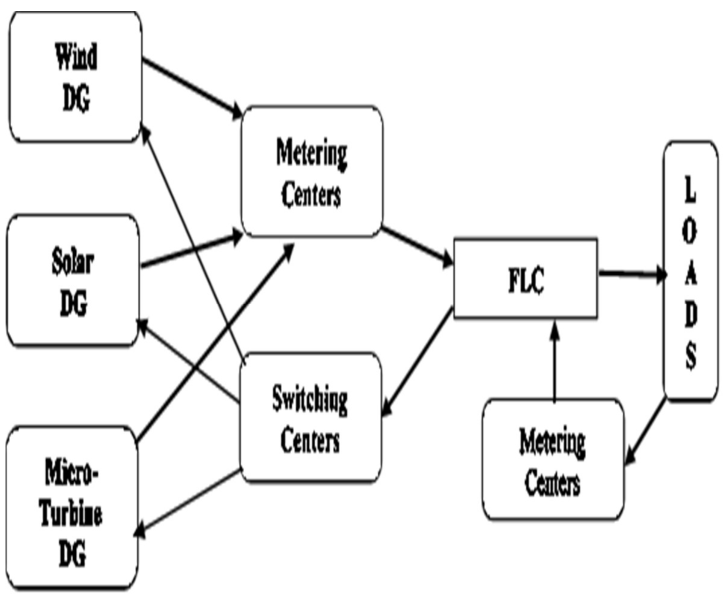


Figure 1 Block Diagram of System

II.1. Modelling of components of Power System Components with DG

Since not all sites are suitable for specific renewable technologies, HOMER software is employed to assess the feasibility of various RES configurations. For wind energy systems, the average annual wind speed is a critical parameter; sites with wind speeds above 5 m/s are generally considered viable for turbine installation. Similarly, for solar PV systems, optimal performance is achieved in regions with an average solar irradiation exceeding 4 kWh/m²/day and a consistent annual radiation profile.

Micro-turbines serve as compact gas turbines that combust gaseous or liquid fuels to generate high-energy gas flows driving an electrical generator. Their ability to start rapidly and support peak load demands makes them particularly valuable in hybrid DG systems, especially for grid-support and backup operations. Consequently, their use in distributed energy networks has grown significantly in recent years.

II.2. Operational Configurations of Distributed Generation

As exemplified in Figure 2, distributed generation (DG) systems operate in 2 prime configurations (modes):

1. Stand-alone and
2. Grid-connected.

Stand-alone Distributed Generation system: In this system power is given directly to local loads through a low-voltage distribution bus. These systems often include battery storage units to ensure continuous power availability during fluctuations in generation or load demand. However, in certain configurations such as directly coupled systems—battery storage may be omitted when generation and load conditions are well matched.

Grid-connected Distributed Generation system: When connected to the grid, distributed generation units connect to the traditional power system through medium-voltage (MV) or low-voltage (LV) distribution lines. The lines are chosen based on the unit's rated capacity and voltage needs. In addition to providing active power to nearby loads, these DG units can also help with reactive power compensation and voltage regulation. This helps keep the grid stable and makes the whole system work better.

Grid-connected DG systems can be set up with or without backup power capabilities, depending on how reliable you want them to be. No matter how they are set up, they must follow strict operational and performance standards when they are added to the utility network. These standards include limits on voltage deviation, frequency synchronization, and harmonic distortion. Following these grid codes makes sure that DG units work safely, efficiently, and in harmony with modern power networks.

III. FUZZY CONTROLLERS IMPLEMENTED IN SYSTEM

This paper employs a fuzzy logic controller (FLC) based on the Mamdani inference method, chosen for its robustness and adaptability in complex control applications. The Mamdani approach is particularly advantageous for managing nonlinear and intricate systems without requiring precise mathematical modeling or analytical derivation. Moreover, fuzzy logic offers high flexibility—when system parameters or operating conditions change, the controller can be readily adjusted without complete redesign. Additionally, fuzzy logic can be effectively integrated with conventional control techniques to enhance their efficiency, simplify tuning, and improve overall system performance. These attributes make the Mamdani-based FLC a suitable choice for distributed generation system optimization.

$$R^{(k)}: IF\ x_1\ and\ x_2\ is\ F^k,\ then\ y_1\ is\ G^k, for\ k = 1,2, \dots \dots, n \qquad (1)$$

Where,

x_1- Altered DGs power capacity in per unit (p.u.),

x_2- the distance in kilometers (Km) between the changed DG sources and the loads

y_1- priority level of assigning the best source to the right load

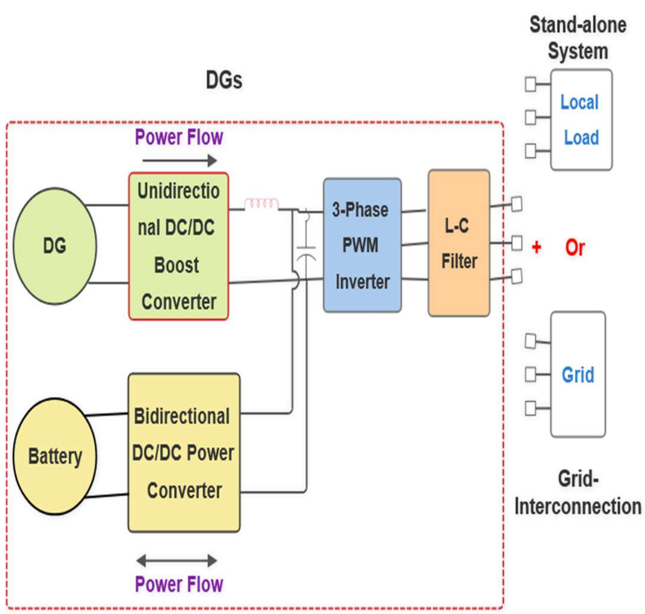
Where,

$x_1, x_2 \dots x_n$ ε u, and y_1 ε R are the input and output of fuzzy sets in U_1, U_2

R representing the kth precursor pairs and decisions pair resp. and n is the rules numbers.

In the proposed system input (I/P) and output (O/P) variables are represented using two types of membership functions: the first type adopts a triangular form, as defined by equation (2), and the second adopts a trapezoidal form, as outlined in equation (3). The membership functions for both input and output are illustrated in Figure 3.

$$trimf\ (x; a, b, c) = \max\left(min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \qquad (2)$$



.**Figure 2** Twin Mode Operation of DGs

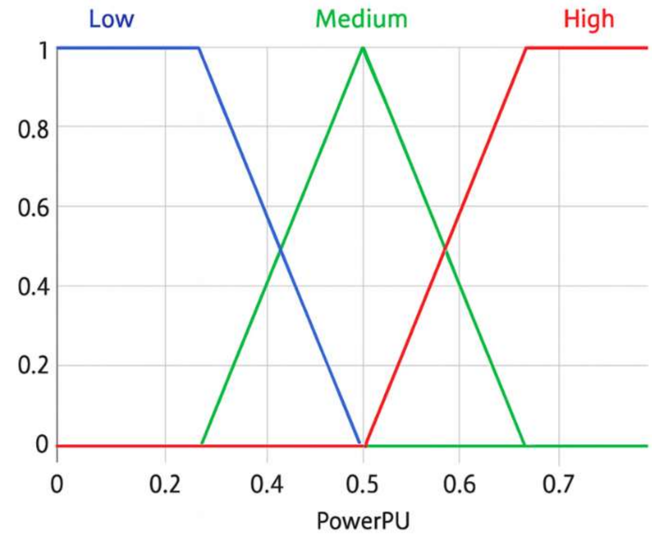


Figure 3 Fuzzy Member Functions (Input and output)

IV. ALGORITHM PROPOSED AND SIMULATION RESULTS

The fuzzy algorithm proposed for distributed generation (DG) power networks in this study is illustrated in Figure 4. The flowchart begins with interpreting the power capacity levels of all available DG units and the distances between these DGs and their respective loads, based on data collected from smart meters.

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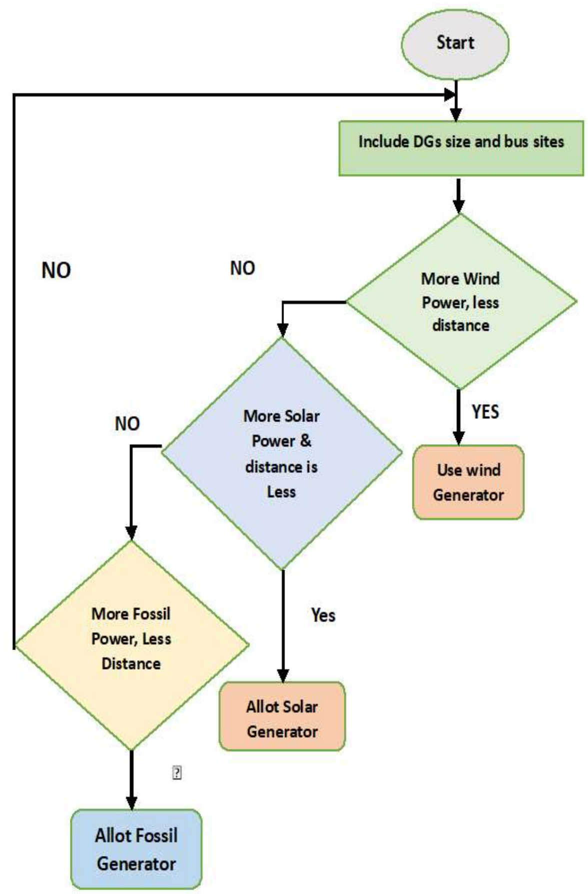

Figure 4 Fuzzy Algorithm Implementation

IV.1. Rule Base Design for the Fuzzy Logic Controller (FLC)

As per previous discussion, the base of the Fuzzy Logic Controller (FLC) is in the construction of its rule base. The rule sets of the proposed algorithm are explained by equations (4), (5), and (6). Table 1 indicates an assortment of rule base of FLC of this system where:

- If the available wind power is high and the corresponding load center is located at a short distance, then the Wind DG unit should be prioritized.
- If the available solar power is high and the distance to the load center is low, then the PV DG unit should be selected.
- If the available fossil-fuel generation capacity is high and the distance to the load center is low, then the Fossil DG unit should be assigned.

However, Table 1 also highlights scenarios in which two or more DG types share similar power capacities and distances. This overlap presents a challenge for the proposed technique, necessitating a refined approach. To rectify this, the FLC can be improved by adding a different parameter, like the cost of the electrical power generated, to better prioritize DGs with lower costs.

Table 1: Fuzzy Rule Base for DG Priority Allocation

Power Capability	Distance	DG Priority Allocation
Low	Low	Low
Low	Medium	Low
Low	More	Low
Medium	Low	Medium
Medium	Medium	Low
Medium	More	Low
More	Low	More
More	Medium	Medium
More	More	Low

In such cases, the distributed generation (DG) source with the highest power capability, shortest distance to the load, and lowest generation cost will be prioritized and allocated to the load first.

IV.2. Transition from Centralized to Distributed Energy Systems

Global energy consumption is projected to increase by approximately 57% over the next two decades. Consequently, a substantial expansion in installed generation capacity will be necessary to meet the rising global electricity demand. Estimates suggest that total worldwide electricity generation capacity could reach 5,495 GW by 2025.

To address the growing energy deficit and overcome the limitations of conventional centralized generation methods, the integration of renewable distributed generation (DG) technologies into modern power grids has accelerated significantly. These systems offer numerous advantages, including enhanced efficiency, reduced transmission losses, improved reliability, and lower environmental impact. The increasing economic competitiveness and technological maturity of DG systems further strengthen their adoption as viable alternatives to traditional generation methods [25].

Table 2: Modest DGS Technologies Comparison

Technology	Wind Turbine	Solar Arrays	Fuel Cells	Micro-Turbine
Size (Output Produced)	0.0003 to 5 MW	0.0003 to 2 MW	0.001 to 10 MW	0.025 to 0.5 M41W
Installation Cost (₹/KW)	80000-4,00,000	4,80,000-80,00,000	80,000-4,00,000	1,00,000-1,40,000
Operation & Maintenance Cost (₹/Kwh)	4-13	12-15	4	16
Electrical Efficiency	25-35%	35-65%	25-45%	05-20%
Overall Efficiency	75-80%	80-90%	25-45%	05-20%
Type of fuel	Wind	Sunlight	Natural gas, Hydrogen and Hydrogen based fuels	Natural gas, liquid fuels

HOMER software was utilized to analyze wind and solar energy data, as illustrated in Figures 5a and 5b, in order to demonstrate the effectiveness of this study. The proposed system was modeled and implemented in HOMER, as depicted in Figure 6.

Upon simulation, HOMER generated a list of various system configurations, which were sorted according to their total net present cost (NPC) [25–30]. In this case, the proposed scenario resulted in thirty-six distinct configurations, organized by the lowest total NPC. However, as summarized in Table 3, the software highlighted the top four configurations as the most optimal solutions.

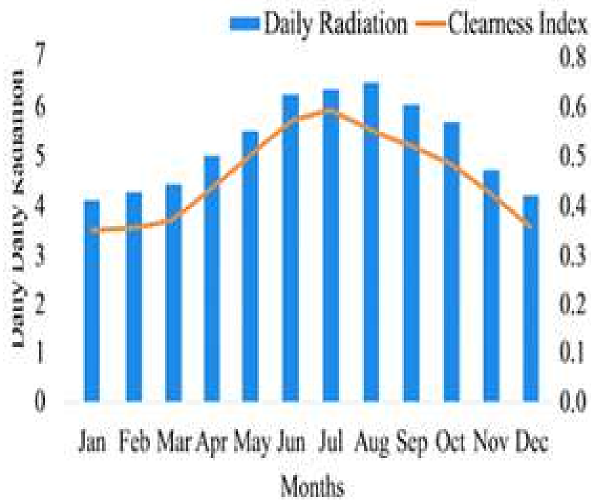

Figure 5 Daily Solar Radiation Record of 1 Year

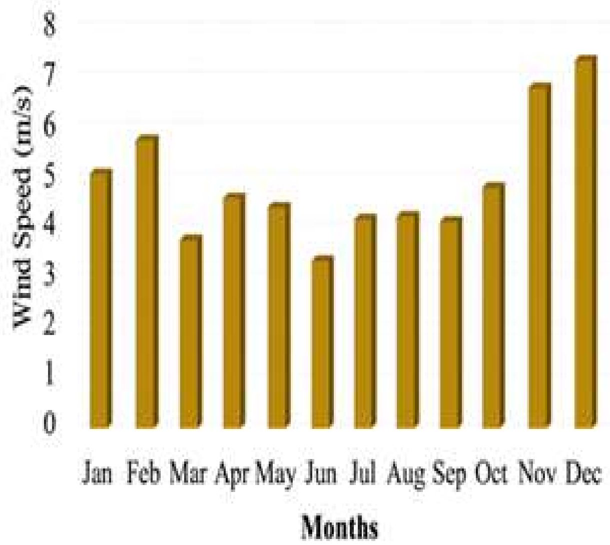

Figure 6 Monthly Wind Speed Record of 1 Year

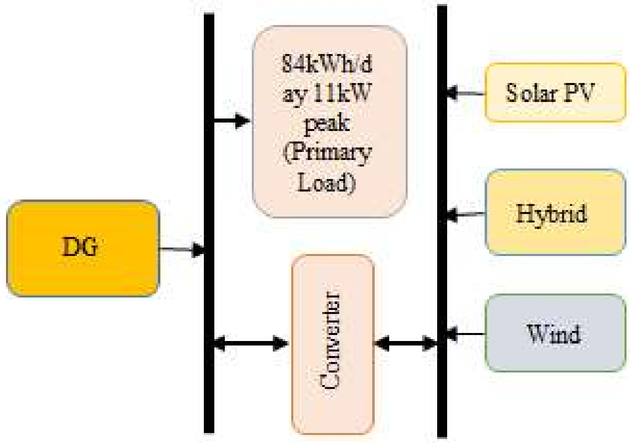

Figure 7 DG system Designed by HOMER

To evaluate the performance of the proposed systems, configurations A and B were compared in terms of overall efficiency and economic viability. The analysis revealed that the total Net Present Cost (NPC) of Configuration A was ₹11,697,940, whereas Configuration B demonstrated a lower NPC of ₹11,137,776, indicating improved cost-effectiveness. A detailed comparison of the electrical energy production and sustainability metrics for both configurations is presented in Table 3.

Table 3: DGS Configuration A & B Comparison

PHASE	**CONFIGURATION A**	**CONFIGURATION B**
USED DGS	WIND + SOLAR + MT (DIESEL GEN.) + BATTERIES	WIND + MT (DIESEL GEN.) + BATTERIES
TOTAL NPC (₹)	1,16,97,940	1,11,37,776
WIND (%)	70	74
SOLAR (%)	6	0
DIESEL (%)	24	263
COE/KWH(₹)	33	31
EXCESS ELEC. (%)	30	28
CO_2 EMISSION (KG/YR)	@18,000	@ 20,000

Table 3 presents a comparative analysis of Configurations A and B in terms of technical, economic, and environmental performance. Configuration A integrates wind, solar, microturbine (diesel generator), and battery storage, whereas Configuration B employs only wind, diesel generation, and batteries. The total Net Present Cost (NPC) of Configuration A was estimated at ₹11,697,940, slightly higher than Configuration B's ₹11,137,776, indicating that the latter offers a modest cost advantage.

In terms of energy contribution, wind power accounted for 70% and 74% of total generation in Configurations A and B, respectively. Solar energy contributed 6% in Configuration A but was absent in Configuration B. Diesel generation played a greater role in Configuration B (26%) compared to Configuration A (24%), reflecting the reduced renewable share. Consequently, Configuration B exhibited a marginally lower cost of energy (₹31/kWh) compared to Configuration A (₹33/kWh).

From an environmental perspective, Configuration A produced lower annual CO_2 emissions (approximately 18,000 kg/year) compared to Configuration B (around 20,000 kg/year), highlighting the sustainability advantage of integrating solar generation. Both systems generated a moderate amount of excess electricity 30% in Configuration A and 28% in Configuration B suggesting similar overall energy balance characteristics.

V. CONCLUSION

This paper describes an optimum fuzzy approach for DG in electrical power distribution systems that incorporates wind and solar resources into traditional electric networks. The fuzzy controller is intended to select the appropriate DG source and assign it to the load. As previously stated, DG technologies present very different research challenges than traditional centralized power sources. Lower cost, higher efficiency, and longer life-time DGs are among these research issues. Finally, HOMER software is employed to determine the best DG configurations based on total NPC.

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