Analysis of Renewable Energy Sources and Electric Vehicle Integration Into Microgrid Using Fuzzy Logic Based Control

Dr. S. Kumar [1], B. Kavitha[2], CH. Vamsi [3], B. Haritha [4]

[1]*Assistant Professor, Dept. of Electrical and Electronics Engineering, JNTUH UCEM, Telangana, INDIA*
[2]*Student, Dept. of Electrical and Electronics Engineering, JNTUH UCEM, Telangana*, INDIA
[3]*Student, Dept. of Electrical and Electronics Engineering, JNTUH UCEM, Telangana, INDIA*
[4]*Student, Dept. of Electrical and Electronics Engineering, JNTUH UCEM, Telangana, INDIA*

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Abstract - *Due to the intermittent nature of renewable generation and the dynamic load behavior of EVs, integrating renewable energy sources and EVs into microgrids presents substantial problems for maintaining system stability, power quality, and effective energy management. In order to improve the performance of a microgrid that consists of photovoltaic (PV), wind energy systems, a diesel generator, and EVs running in Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) modes, this research suggests a control approach based on fuzzy logic controllers (FLCs). By taking into account changes in renewable generation, EV battery charge levels, and load situations, the FLC is built to control power flow, preserve voltage stability, and balance load demand. The suggested method successfully manages system uncertainties and does not require exact mathematical modeling, in contrast to conventional controllers. MATLAB/Simulink simulation results show that the FLC-based system decreases power fluctuations, minimizes harmonic distortion, improves voltage regulation, and increases overall system approach offers an effective and flexible option for smart microgrid control.*

Key Words: *Microgrid, Fuzzy Logic Controller (FLC), Electric Vehicles, Vehicle to Grid (V2G), Renewable Energy, Power Quality.*

1. INTRODUCTION

The growing use of electric vehicles (EVs) and the incorporation of renewable energy sources, especially in microgrid situations, have significantly changed modern power networks. EV adoption as a greener substitute for traditional transportation systems has accelerated due to growing concerns about greenhouse gas emissions and environmental sustainability [1], [2]. EVs are eco-friendly and contribute significantly to the development of sustainable energy systems and smart grids [3], [4].

Microgrids have become a successful way to combine EVs and renewable energy sources, allowing for more operational flexibility, increased dependability, and localized energy generation. To effectively deliver power to local loads, these systems integrate distributed energy resources such solar photovoltaic systems, wind energy systems, and conventional generators [5], [6]. Additionally, EVs can contribute to load balancing, peak shaving, and grid support by acting as both loads and distributed energy resources using vehicle-to-grid (V2G) technology [7], [8].

However, there are a number of technical difficulties when combining EVs with renewable energy sources. Power generation and load demand are unclear due to the sporadic nature of renewable energy supply and the stochastic behavior of EV charging [9], [10]. Power quality problems such voltage instability, harmonic distortion, load imbalance, and power flow fluctuations are caused by these uncertainties and impair system performance and dependability [11], [12].

Moreover, harmonic components introduced by power electronic converters in EV charging infrastructure have an additional impact on power quality and system stability[13]. Current energy management and control solutions are limited in their ability to handle nonlinear and uncertain system behavior because they frequently rely on exact mathematical models. Particularly in microgrids with high penetration of renewable energy and EVs, many traditional approaches fall short of providing optimal performance under dynamic operating conditions [16], [17]. While a number of optimization and coordinated charging strategies have been put forth, they mostly concentrate on certain goals like load scheduling or cost minimization and do not fully address power quality and system stability challenges at the same time [18]-[20].

This research suggests a sophisticated energy management approach based on a fuzzy logic controller (FLC) for microgrid applications in order to get beyond these restrictions. Without the need for a precise mathematical model, fuzzy logic control offers a resilient and adaptable framework that can handle nonlinearities and uncertainties. The suggested FLC is intended to balance load demand, reduce harmonic distortion, enhance voltage regulation, and preserve steady power flow inside the microgrid.

Additionally, the suggested method makes it possible to efficiently coordinate grid operations, EV charging systems, and renewable energy sources. The FLC guarantees optimal use of existing energy resources, improves dynamic response, and strengthens system resilience by integrating intelligent decision-making.

This paper's primary contributions consist of:

(i) creating an energy management system for microgrid operation based on FLC,

(ii) enhancing power quality metrics while integrating EVs and renewable energy sources; and

(iii) comparing performance with traditional control techniques.

When compared to conventional control methods, simulation results show that the suggested FLC-based strategy greatly improves power quality, lowers disturbances, and boosts overall system performance. These findings demonstrate how well intelligent control techniques can handle the difficulties of integrating EVs and renewable energy sources into contemporary microgrid systems.

1.1 LITERATURE REVIEW

The significance of electric vehicles (EVs) in promoting the integration of renewable energy sources and enhancing grid flexibility through sophisticated control and charging techniques has been examined in recent research [21]–[24]. In addition to serving as dispersed energy sources, EVs can offer auxiliary services like load balancing and frequency management. However, there are major issues with load fluctuation, peak demand, and system stability when they are integrated on a wide scale [25], [26].

A number of optimization-based strategies have been put forth to control EV charging and boost system effectiveness. These techniques frequently overlook crucial elements like voltage stability, network losses, and overall microgrid performance in an effort to lower charging costs and flatten load profiles [27], [28].

Furthermore, harmonic distortion, voltage dips, and phase imbalance are introduced by the usage of power electronic converters in EV charging infrastructure, which deteriorate power quality and impact system dependability [29]–[31]. Higher network losses and shorter distribution component lifespans are further consequences of increased EV penetration [32].

Despite these developments, the majority of current techniques are less successful in managing nonlinear and unpredictable system conditions since they concentrate on single-objective optimization and depend on precise mathematical models. Fuzzy Logic Controllers (FLCs) provide an adaptable and reliable way to get around these restrictions by controlling system uncertainties without the need for exact modeling. The suggested FLC-based method offers a complete solution for EV-integrated microgrid systems by simultaneously improving voltage control, harmonic suppression, load balancing, and power flow stability.

1.2 SYSTEM DESCRIPTION

The below fig1 is a schematic diagram that describes about the hybrid microgrid which combines electric vehicles (EVs), renewable energy sources, and intelligent control to successfully handle problems brought on by intermittent generation and dynamic demand fluctuations. The main clean energy sources are solar photovoltaic (PV) and wind energy systems, which lessen reliance on fossil fuels and their negative effects on the environment. However, because of their unpredictability, a diesel generator is included to provide a steady power supply in times of low renewable output and abrupt load fluctuations.

By allowing EVs to function as distributed energy storage units, the incorporation of Vehicle-to-Grid (V2G) technology significantly improves system performance [36]. EVs have the ability to store extra energy during times of low demand and return it to the grid during times of high demand. Consequently, load balancing is supported, total system efficiency is increased, and dependency on traditional generation sources is decreased.

In this fuzzy logic controller (FLC) is used to control the microgrid's nonlinear and unpredictable behavior. Because fuzzy logic-based control systems can handle nonlinearities and uncertainties without the need for exact mathematical models, they are frequently used in microgrid energy management [55],[57]. Effective coordination between load demand, EV charging and discharging, and renewable generation is made possible by the FLC, which improves voltage stability, lowers harmonic distortion, and facilitates smoother power flow throughout the system. Furthermore, when compared to traditional control techniques, FLC-based systems have shown improved system performance and robustness [56]

All things considered, the suggested system offers a dependable, effective, and sustainable solution for modern microgrid applications, enhancing power quality and facilitating the shift to intelligent and renewable energy-based power systems.

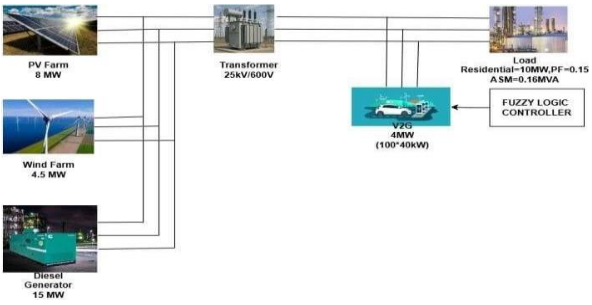

Fig-1: Schematic diagram of microgrid and electric vehicle

A. Mathematical Equations

The power equations for the distribution system are based on below one:

$P_{load}(K)+P_{loss}(K)=P_{gen}(k)+F(e(k), \Delta e(k))$

Where,

- $P_{load}(k)$is power required by consumers
- $P_{loss}(k)$ is losses
- $P_{gen}(k)$ is generated power
- $F(e,\Delta e)$ is output of fuzzy logic controller

$P_{gen} = P_{pv}+ P_{wind} +P_{ev} +P_{DC}$

1. CHALLENGES OF ELECTRIC VEHICLE AND V2G OPTIMIZATION

By enhancing decision-making under uncertainty and managing nonlinear properties, the incorporation of a fuzzy logic controller (FLC) improves the performance of electric vehicle (EV) systems. Nevertheless, despite these benefits, a number of operational, technological, infrastructural, and financial obstacles still stand in the way of efficient EV deployment and Vehicle-to-Grid (V2G) optimization, especially in the Indian setting.

1. Grid-related and Technical Difficulties

Existing power systems are being strained by the widespread integration of EVs. EV charging results in:

- Variations in voltage
- Distortion of harmonics
- unbalance in three phases

These problems impact grid stability and deteriorate power quality. FLC can control charging methods, but it cannot completely remove infrastructure and physical grid restrictions.

2. Uncertainty in Patterns of EV Use

The availability of grid-connected EVs is critical to V2G optimization. But:

- EV charging behavior is erratic and user-driven.
- Travel habits are erratic.

Even with intelligent controllers like FLC, this uncertainty makes it challenging to create trustworthy optimization algorithms.

3. User Reluctance and Battery Degradation

In V2G activities, frequent rounds of charging and draining result in:

- Increased wear on batteries
- shorter battery life

The usefulness of the system may be limited as a result of EV owners' reluctance to engage in V2G initiatives.

4. Multi-Objective Optimization Complexity

V2G systems must concurrently maximize several competing goals:

- Minimization of costs
- Grid stability, load balance, and battery health

This increases the computing load and implementation difficulty by creating a complicated, multi-objective optimization problem.

5. India's Inadequate Charging Infrastructure

India has serious infrastructure deficiencies, such as:

- Public charging facilities are scarce.
- Absence of V2G-capable bidirectional chargers
- Low adoption of smart grid technology

The practical implementation of V2G systems is limited by these constraints.

6. Variability in Renewable Energy

Renewable energy sources like solar and wind are frequently combined with EV integration. But:

- These sources rely on the weather and are sporadic.
- This makes power availability more unreliable.

Even when FLC is used, such variability makes control measures more difficult.

2. RESULTS AND DISCUSSION

This Fig 2 describes about a hybrid microgrid that combines several energy sources with a clever control method for effective power management. A shared bus and a 25 kV/600 V transformer connect the 8 MVA photovoltaic (PV) system, 4.5 MW wind farm, and 15 MW diesel generator. While the diesel generator guarantees dependability during power shortages, the PV and wind systems function under a variety of environmental situations. One hundred electric vehicles make up a 4 MW Vehicle-to-Grid (V2G) system that allows bidirectional power transfer to facilitate load balancing. V2G operation is controlled by a fuzzy logic controller (FLC), which minimizes power fluctuations, lowers harmonics, and improves voltage stability.

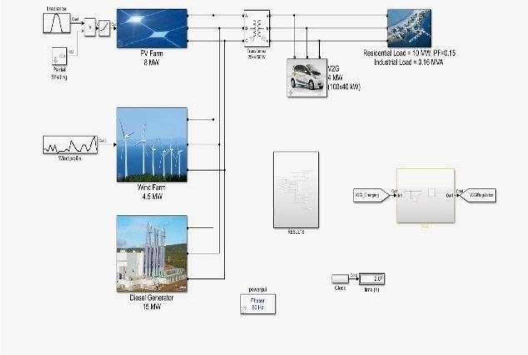

Fig-2: Simulation diagram

An effective and dependable smart microgrid energy management system is demonstrated by the system, which provides both residential and industrial loads and is simulated in a phasor-based environment at 60 Hz.

Power generated by solar, wind, diesel, total power generated, and load drawn power are shown below.

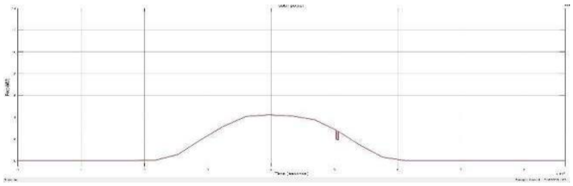

Fig-3: Power generated by the solar throughout the day

In fig 3, at first, there is no generation because the solar power output is zero. After it increases quickly, peaking at 4–4.2 MW as a result of the most sunlight. Following the peak, there is a small disruption about mid-time before the power steadily drops. At last, it returns to zero, indicating that there is no solar generation. This illustrates how solar energy is typically time-dependent.

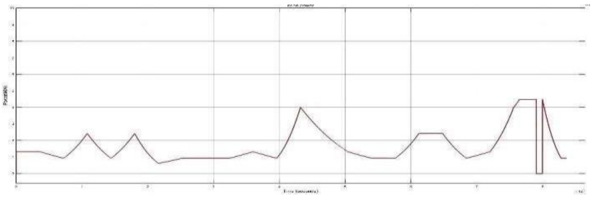

Fig-4: Power generated by the wind throughout the day

In the fig 4, over time, the wind power output exhibits notable fluctuations, with low values of approximately 0.8 MW and peaks of approximately 4–4.5 MW. It highlights the erratic and sporadic character of wind energy with abrupt increases and decreases, even momentarily approaching zero.

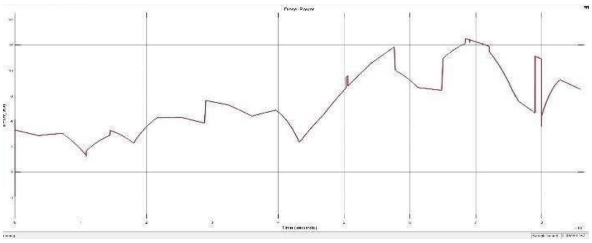

Fig-5: Power generated by generator throughout the day

In fig 5 ,the diesel generator output varies with load demand, starting at a stable level around 5 MW, increasing to a peak of about 12–13 MW during high demand, and then dropping before stabilizing again. This shows good load-following capability, quick response, and stable performance.

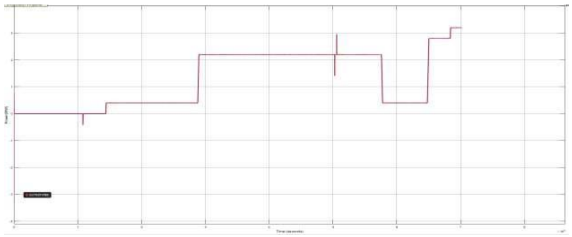

Fig 6: Charged and regulated into microgrid throughout the day

In the fig 6, the first low activity is shown by the EV power starting close to nothing. Due to increased charging demand, it then gradually grows to around 0.5 MW and finally rises to about 2.2 MW. Around mid-time, fluctuations start to exhibit signs of dynamic behavior. Reduced demand or discharge is indicated by a dip that happens about 6 seconds. Afterwards, the power rises once further to almost 3 MW. All things considered, EVs are flexible loads with variable power consumption.

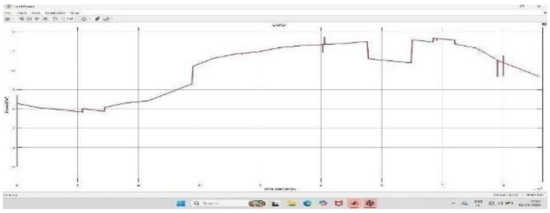

Fig-7: Load drawn power from microgrid during the day

In the fig 6, at first, the load demand is between 6 and 7 MW and then slightly declines. After that, it rises progressively before abruptly surpassing 10 MW at about 3 seconds. The load keeps increasing and eventually reaches 12–13 MW. After a brief decline of around six seconds, there is a recovery and stabilization at higher levels. This suggests a dynamic pattern of rising load over time.

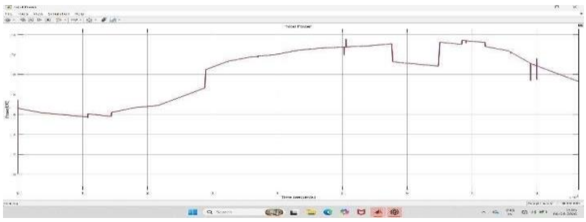

Fig-8: Total power generation from microgrid during the day

In the fig7, at first, there is a small decline in the total power, which begins at about 6-7 MW. After that, it rises progressively before abruptly rising above 10 MW for around three seconds. The power keeps increasing and eventually reaches 12–13 MW. After five to six seconds, there is a slight decline and then a comeback. At increasing levels, it eventually stabilizes. This shows that power and load demand are effectively balanced.

4. CONCLUSION

The proposed FLC-based hybrid microgrid successfully combines diesel production, renewable energy sources, and V2G technology to guarantee steady and effective power management under changing circumstances. In comparison to the base scenario, the system greatly improves voltage regulation and overall operational stability by maintaining a strong balance between generation and load. By lowering harmonic distortion, improving power quality, and facilitating effective peak load management through coordinated V2G operation, the fuzzy logic controller minimizes reliance on diesel production and lowers operating expenses and emissions. Reduced losses and increased system resilience are further benefits of enhanced reactive power supply and quick dynamic response. All things considered, the suggested method offers a scalable, dependable, and sustainable option for contemporary smart grids and upcoming distributed energy systems.

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