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Analyzing The Impact of Electric Vehicle Charging on Grid Congestion and Load Management

Tej Pratap Singh[1], Ashish Bhargava[2]
[1] Research Scholar, tp.singh1294@gmail.com, EE BERI, Bhopal, India
[2]HOD, EE BERI, Bhopal, India

Abstract *– The surge in environmental and energy concerns has spurred the adoption of Electric Vehicles (EVs), which are rapidly advancing despite various challenges. Key obstacles include the need to improve driving range, battery longevity, and power capacity. To tackle these issues, this thesis investigates the performance of EVs equipped with a Hybrid Energy Storage System (HESS) that combines Li-ion batteries and Ultracapacitors (UCs). A comprehensive model of various system components for a 3-wheeled Electric Vehicle (EV), based on the Indian Driving Cycle (IDC), is presented to assist in sizing the Energy Storage System (ESS).*

Efficient energy management control is essential for regulating power flow according to the drive cycle's load requirements. This necessitates a robust control design capable of accommodating real-time load fluctuations by regulating power flow from hybrid sources. The thesis proposes a hybrid control strategy integrating filtering and fuzzy rule-based techniques for effective power flow regulation. Results regarding various performance metrics, including battery stress factor, UC state-of-charge (SOC) difference, energy consumption rate, system efficiency, and speed profile tracking, demonstrate the satisfactory performance of the proposed control strategy.

A comprehensive comparative study of EVs employing Battery Energy Storage Systems (BESS) and hybrid energy storage systems is presented to elucidate the advantages of HESS. Economic feasibility assessments of BESS and HESS underscore the effectiveness of Li-ion battery/UC HESS.

Keywords: Electric Vehicle, Battery Energy Storage System, Hybrid Energy Storage System, Ultra Capacitor, Convertor, State of Charge.

I. INTRODUCTION

The rapid adoption of electric vehicles (EVs) is transforming the global transportation sector, driven by advancements in battery technology, government incentives, and growing environmental concerns. While EVs offer a sustainable alternative to internal combustion engine (ICE) vehicles by reducing carbon emissions and dependence on fossil fuels, their increasing penetration poses significant challenges to the existing power grid infrastructure. One of the most pressing concerns is grid congestion and load management, as the widespread and uncoordinated charging of EVs can lead to voltage fluctuations, transformer overloading, and peak demand surges. As a result, understanding the impact of EV charging on the electrical grid is critical to ensuring grid stability, energy efficiency, and optimal power distribution.

Electric vehicle charging patterns vary based on factors such as charging station availability, charging speed (Level 1, Level 2, or DC fast charging), driver behavior, and time-of-use electricity tariffs. The unpredictable nature of EV charging, particularly during peak hours, can result in localized grid congestion and cause voltage instability in certain regions. In urban areas with a high concentration of EV users, uncoordinated charging can overload distribution transformers and substations, leading to increased operational costs for utilities and the need for expensive infrastructure upgrades. Conversely, the strategic deployment of smart charging algorithms, demand response programs, and vehicle-to-grid (V2G) technology can mitigate these challenges by enabling bidirectional energy flow, optimizing power distribution, and supporting renewable energy integration.

This study aims to analyze the impact of EV charging on grid congestion and load management, focusing on key aspects such as charging demand forecasting, peak load mitigation strategies, and the role of smart grid technologies in addressing grid challenges. Various machine learning (ML) and optimization techniques have been proposed to predict EV charging demand and improve grid resilience. Additionally, blockchain-based decentralized energy trading, artificial intelligence-driven predictive load balancing, and adaptive time-of-use pricing mechanisms are emerging as potential solutions for enhancing grid efficiency.

The research investigates the following critical questions: How does EV charging behavior impact the stability of the power grid? What are the potential mitigation strategies for reducing grid congestion? How can smart grid technologies and AI-driven solutions contribute to better load management? By addressing these questions, this study provides data-driven insights and strategic recommendations for power utilities, policymakers, and

EV infrastructure planners to develop sustainable and efficient EV-grid integration frameworks..

II. PROPOSED METHOD

Fuzzy logic, a type of many-valued logic, enables the representation of truth values of variables as any real number between 0 and 1. This approach is particularly useful in scenarios involving partial truth, where a value does not need to be entirely true or false but can lie anywhere on the spectrum from completely true to completely false. In contrast, Boolean logic restricts truth values to two discrete states: 0 (false) or 1 (true).
The concept of fuzzy logic was first introduced by Lotfi Zadeh, an Iranian-Azerbaijani mathematician, in 1965 as part of his work on fuzzy set theoryThe origins of fuzzy logic can be traced back to the 1920s, when researchers like Łukasiewicz and Tarski examined the connection between infinite-valued logic and fuzzy logic.

Fuzzy logic is grounded in the idea that human decision-making often relies on vague or non-numerical information. To represent this imprecision, fuzzy models and fuzzy sets are used as mathematical tools. These models enable the recognition, representation, processing, and interpretation of ambiguous or uncertain data. This ability makes fuzzy logic an effective framework for addressing real-world complexities that binary logic systems struggle to represent.

Characteristics of Fuzzy Logic

Following are the characteristics of fuzzy logic:

- **Flexibility and Ease of Use**:

Fuzzy logic is inherently flexible, making it straightforward to understand and apply across various fields. Its adaptability allows for seamless integration into different systems and scenarios.

- **Reduction of Human-Defined Logic**:

By minimizing reliance on manually crafted rules and logic, fuzzy logic simplifies complex problem-solving processes.

- **Ideal for Approximate Reasoning**:

Fuzzy logic excels in situations where precise reasoning is challenging, offering a robust framework for handling approximate or uncertain data.

- **Dual-Value Solutions**:

It consistently provides solutions with two values, representing the possible outcomes for a given problem or statement.

- **Capability to Create Complex Non-Linear Functions**:

Users can leverage fuzzy logic to define or generate non-linear functions of any desired complexity, making it versatile for advanced computational tasks.

- **Degree-Based Framework**:

In fuzzy logic, everything operates on a scale or degree, representing varying levels of truth instead of fixed binary values.

- **Integration with Other Logical Systems**:

Fuzzy logic can easily incorporate or adapt existing logical systems, enhancing their functionality without requiring extensive modifications.

- **Foundation in Natural Language Processing (NLP)**:

Natural language serves as the basis for fuzzy logic, enabling effective interaction and interpretation of linguistic expressions.

- **Application in Quantitative Analysis**:

Quantitative analysts often use fuzzy logic to optimize and refine algorithm performance, particularly in dynamic and uncertain environments.

- **Enhanced Connectivity**:

Fuzzy logic systems enable users to establish meaningful connections between diverse data points and systems, promoting interoperability and enriched decision-making processes.

Architecture of a Fuzzy Logic System

The structure of the fuzzy logic system gives important consideration to each component. The four elements that make up the architecture are listed below.

- Defuzzification,
- Inference Engine,
- Rule Base, and
- Fuzzification

The architecture or procedure of a fuzzy logic system is shown in the diagram below..

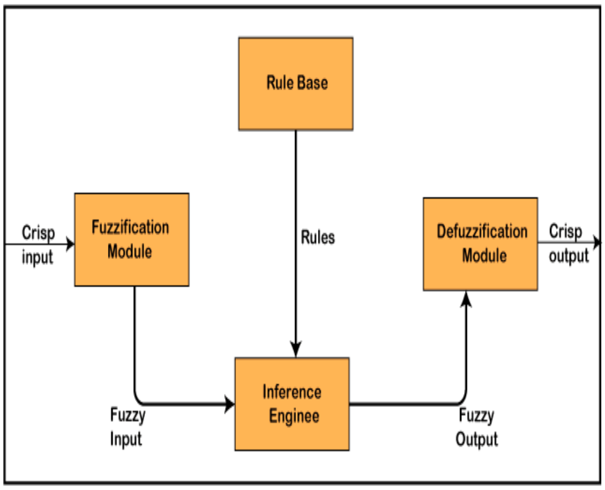

Figure.1 Architecture or process of a Fuzzy Logic system

Figure 2 illustrates the configuration of the Energy Management System (EMS) designed for this study. The EMS is built around a fuzzy logic controller, which forms its central framework. In this setup, the controller also takes on the additional task of managing the State of Charge (SOC) of the Battery Energy Storage System (BESS).
To achieve its objectives, the fuzzy logic system within this EMS is built with three distinct input variables and two output variables. These inputs and outputs are carefully selected to ensure effective decision-making and precise control of the system. The inputs are processed through the fuzzy logic controller, which evaluates them based on predefined rules and

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membership functions, enabling it to generate appropriate outputs. These outputs are then used to regulate the EMS operations, including the BESS SOC, ensuring optimal performance and energy distribution.
This configuration reflects the adaptability and effectiveness of fuzzy logic systems in handling complex energy management scenarios, making it a suitable choice for this study.

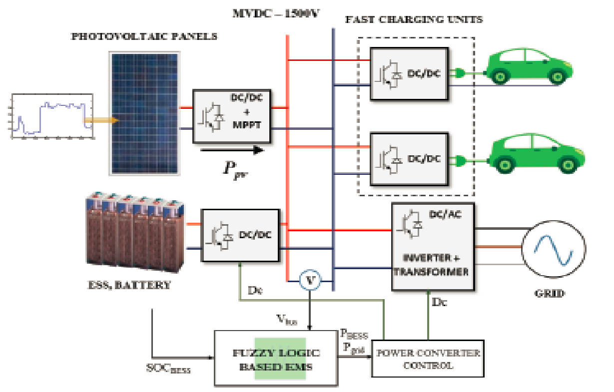


Figure .2 Configuration of the FCS

III. SIMULATION RESULT

Electric Vehicle (EV) charging station is integrated as the primary load of the system. The charging station draws energy from both renewable sources and the BESS, thereby alleviating pressure on the conventional grid. The proposed model supports efficient EV charging while ensuring that the overall energy management system operates within optimal parameters.

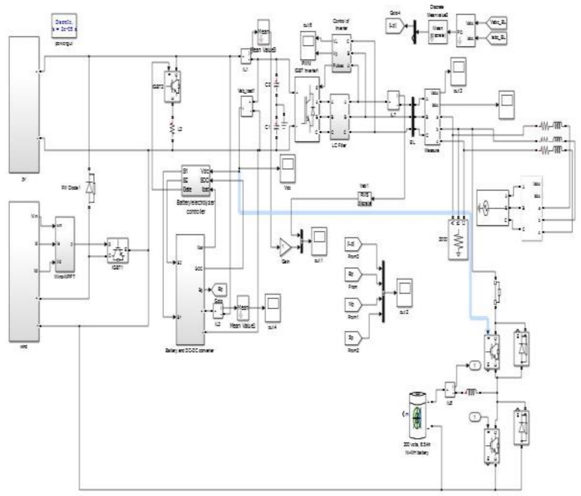


Figure 3: Proposed model

Figure 3 presents the complete proposed model, which is a hybrid power system primarily reliant on renewable energy sources. The system is designed to consistently deliver high-quality output by effectively utilizing these energy sources.
By integrating these components, the proposed model demonstrates a holistic approach to energy generation, storage, and utilization, prioritizing renewable energy sources while supporting EV charging infrastructure. The subsequent simulation results provide insights into the system's performance, validating its effectiveness in balancing energy demand, minimizing reliance on conventional sources, and maintaining stable operations under dynamic load conditions.
The proposed work focuses on designing a hybrid power system that combines a battery energy storage system (BESS), photovoltaic (PV) panels, and wind turbines. This combination ensures a reliable and sustainable energy supply. This section focuses on the results of the proposed model. It includes an in-depth analysis of the system's architecture, evaluating its performance under various operational scenarios, such as changes in the energy sources (source variation) and fluctuations in energy demand (load variation). The results provide insights into the effectiveness and robustness of the hybrid system in managing these variations while maintaining stable and efficient performance.

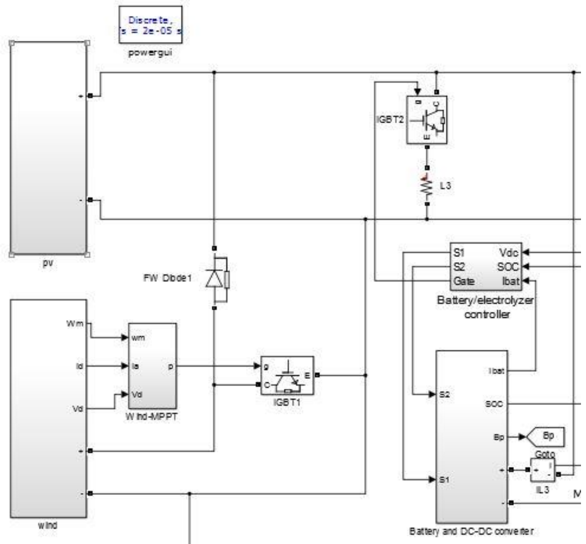


Figure.4: Source section of proposed model

Figure 4 depicts the renewable energy sources integrated with a DC-DC converter and a battery controller. In this configuration, the renewable energy sources act as the primary power source for the system. These sources are connected to a DC-DC converter, which regulates the energy flow, and a battery controller, which manages the charging and discharging of the battery.
The battery controller is specifically designed to operate based on the energy demands of the system. It ensures efficient battery charging when there is excess energy from the renewable sources and supports discharging during periods of high demand. This setup allows the system to meet the main power requirements of the proposed model effectively while ensuring reliability and stability.

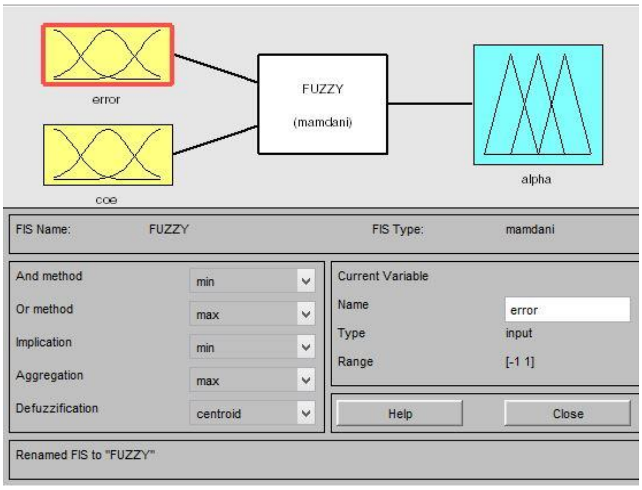


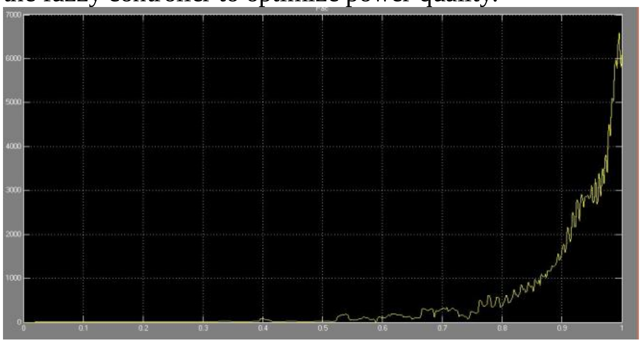
Figure. 5: After the apply fuzzy model in proposed system

Figure 5 shows the window displayed after the initialization phase of the fuzzy logic system, which is utilized to optimize power quality in the proposed model. The system is organized into three main sections:

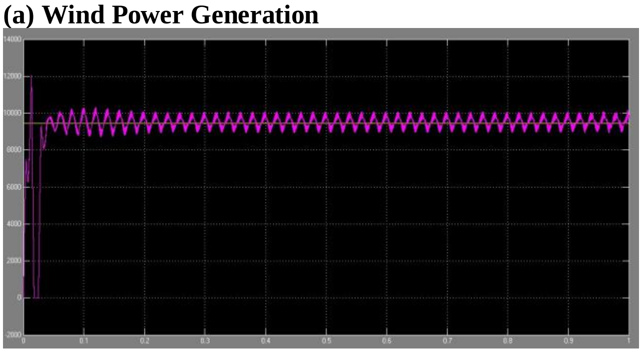
Input Section: This section includes two parameters, namely error and coefficient, which serve as the input variables for the fuzzy logic process.

Fuzzy Controller Section: Located at the center, this section processes the input parameters based on predefined rules and membership functions. It evaluates the variations and applies the corresponding rules to generate the desired output.

Output Section: The output parameter, labeled as alpha, represents the result generated by the fuzzy logic system. This value is derived after processing the inputs through the fuzzy controller to optimize power quality.



(a) Wind Power Generation



(B) PV Power Generation

Figure 6: Power Generation Graph by (a)Wind (b)Solar

Figure 6 illustrates the power generation from renewable energy sources in the proposed model, with the following details:

(a) Wind power generation is recorded at 6133 W.

(b) Solar power generation is recorded at 9464 W.

These values represent the contribution of wind and solar energy to the overall power generation in the system.

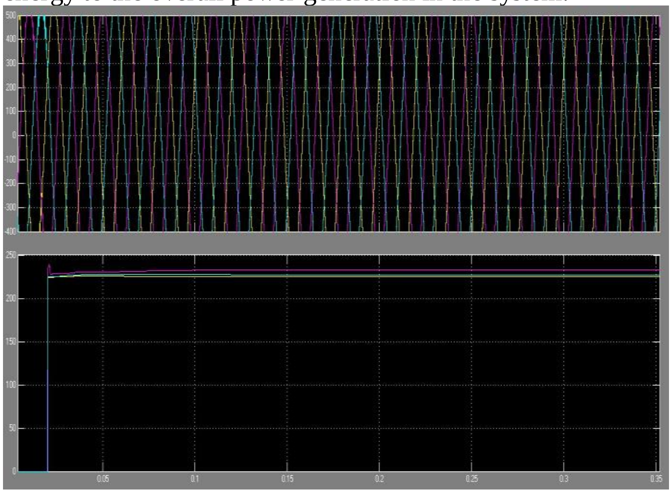
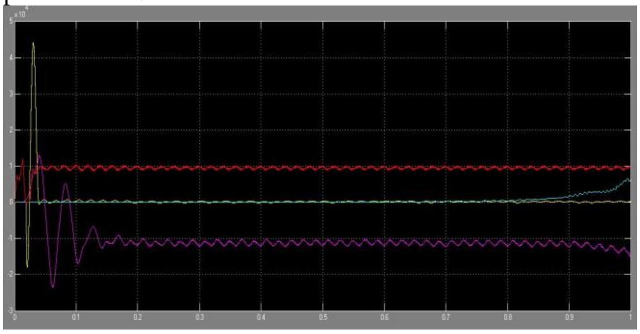
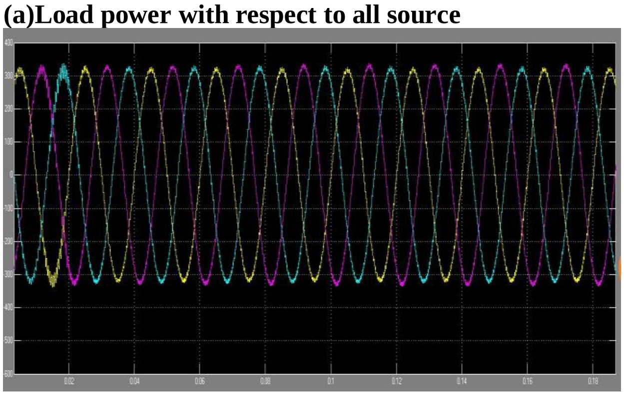


Figure. 7: PWM output of proposed model

Figure 7 depicts the PWM (Pulse Width Modulation) output of the proposed model. In this system, the PWM plays a critical role in regulating the voltage and current levels. The PWM is integrated with a fuzzy logic controller, as described in Figure 5.1, to enhance the power quality of the system. This combination ensures precise control and optimization of the system's performance.



(a)Load power with respect to all source



(b)Voltage

Figure. 8: Load power with respect to all source (a) Load power and source power(b) Output voltage

Figure 8 illustrates the power generation from renewable energy sources in the proposed model along with the load power requirements. The figure highlights the following:

(a) The power required by the charging station compared to the power generated by renewable energy sources.
(b) The stable voltage output achieved through the fuzzy logic controller in the proposed system.
This demonstrates the system's ability to balance power generation and load demand while maintaining stable voltage levels.
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IV. CONCLUSION

This study successfully developed and assessed a hybrid energy management system (EMS) that integrates renewable energy sources, battery storage, and fuzzy logic-based controllers. The proposed model efficiently manages energy generation, storage, and distribution while maintaining stable voltage and power quality under different operational conditions. By incorporating renewable energy sources like photovoltaic (PV) panels and wind turbines, the system reduces reliance on conventional energy sources, fostering sustainability and environmental benefits. The use of a fuzzy logic controller optimized power flow and ensured reliable performance, even with fluctuating load demands and variations in energy sources.

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