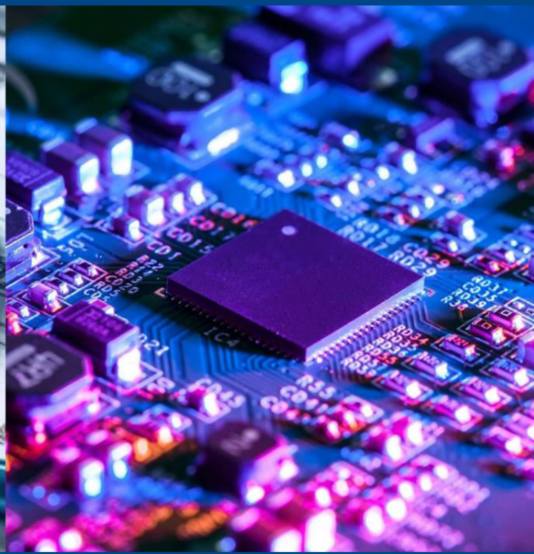
ISSN: 2582-7219





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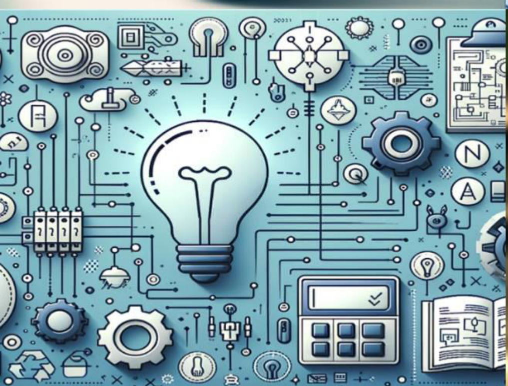

Impact Factor: 8.206

Volume 9, Issue 4, April 2026

ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 8.206| ESTD Year: 2018|

International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

Machine Learning for AC Optimal Power Flow (AC-OPF)

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ABSTRACT: This project presents a machine learning–based approach for solving the AC Optimal Power Flow (AC-OPF) problem on the IEEE 5-bus test system using MATLAB/MATPOWER. AC-OPF is a fundamental power system optimization problem that aims to determine the optimal operating conditions of a power network while minimizing generation cost and satisfying system constraints such as voltage limits, power balance, and line flow limits. Traditional optimization techniques can be computationally intensive, especially for real-time applications.To overcome this, machine learning techniques are explored to approximate the OPF solution more efficiently. The data set is generated using MATPOWER by running multiple load and generation scenarios on the IEEE 5-bus system. A machine learning model is then trained to learn the relationship between system inputs (load demand, generation levels) and optimal outputs (generator set points, voltage profiles, and cost).The trained model is evaluated based on accuracy and computational efficiency compared to conventional OPF solutions. The results show that the proposed approach significantly reduces computation time while maintaining acceptable accuracy, making it suitable for real-time power system operation and smart grid applications

I. INTRODUCTION

The Optimal Power Flow (OPF) problem is one of the most important optimization problems in electrical power systems. It is used to determine the optimal operating conditions of a power network while minimizing the generation cost and maintaining system security and reliability. The AC Optimal Power Flow (AC-OPF) considers both active and reactive power along with practical constraints such as voltage limits, transmission line limits, and generator operating limits, making it more accurate but computationally complex.In this project, the AC-OPF problem is studied using the IEEE 5-bus test system implemented in MATLAB/MATPOWER. The IEEE 5-bus system is a standard benchmark system used for analyzing and testing power system algorithms in a simplified environment. Although it is small in size, it effectively represents the fundamental behavior of real power networks.

Traditional methods for solving OPF, such as nonlinear programming techniques, can be time-consuming and may not be suitable for real-time applications. These methods require iterative calculations and high computational effort, especially when the system size increases or operating conditions change frequently.To overcome these limitations, machine learning techniques are introduced to approximate OPF solutions efficiently. By generating datasets using MATPOWER simulations, the model learns the relationship between system inputs and optimal outputs. This approach significantly reduces computation time and improves efficiency, making it suitable for modern smart grid applications where fast and reliable decision-making is required. Additionally, the proposed method enhances the adaptability of power system operation under varying load conditions.Furthermore, the integration of machine learning with power system analysis enables faster decision-making, improved operational efficiency, and better handling of dynamic conditions. This approach significantly reduces computation time while maintaining acceptable accuracy, making it suitable for modern smart grid applications where real-time monitoring and control are essential.

© 2026 IJMRSET | Volume 9, Issue 4, April 2026| DOI:10.15680/IJMRSET.2026.0904174

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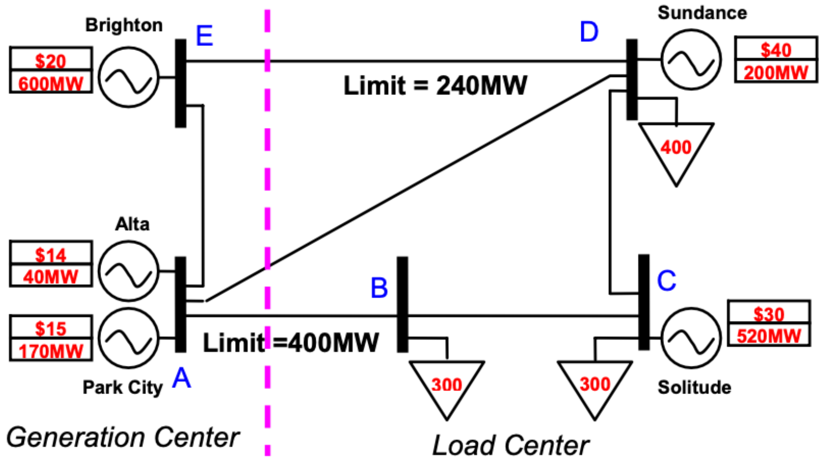

Figure 1: 5-bus grid

The 21st century is widely recognized as the era of digital transformation, where electrical power systems and computational intelligence are becoming increasingly integrated. With the rapid growth of smart grids and advanced optimization techniques, modern power systems require fast and efficient methods for secure and economical operation. One of the most important optimization problems in this field is the Optimal Power Flow (OPF) problem, which plays a key role in determining the best operating conditions of a power network while satisfying all system constraints.The AC Optimal Power Flow (AC-OPF) problem considers both active and reactive power along with practical system limitations such as bus voltage limits, line flow limits, and generator operating constraints. Although it provides accurate results, it is computationally complex and time-consuming when solved using conventional optimization techniques, especially for real-time applications.

To address this challenge, intelligent computational methods are being explored to improve efficiency and speed.In this project, a machine learning–based approach is implemented for solving the AC-OPF problem on the IEEE 5-bus test system using MATLAB/MATPOWER. The IEEE 5-bus system is a standard benchmark model used for analyzing power system behavior in a simplified environment. By generating datasets from MATPOWER simulations, the machine learning model learns the relationship between system load conditions and optimal control variables.This approach reduces computation time significantly while maintaining acceptable accuracy, making it highly suitable for modern smart grid applications where fast decision-making is essential.

II. LITERATURE REVIEW

A critical assessment of the existing work has been carried out in the field of Optimal Power Flow (OPF) and the application of intelligent techniques for solving power system optimization problems. The OPF problem plays a crucial role in power system operation as it determines the optimal generation schedule while satisfying system constraints such as voltage limits, power balance, and transmission line constraints. With the increasing complexity of modern power systems, researchers have explored various mathematical and computational approaches to improve the efficiency and speed of OPF solutions.

J. Carpentier [1] proposed the fundamental formulation of the Optimal Power Flow (OPF) problem in electrical power systems, which laid the foundation for modern power system optimization studies. The author introduced a mathematical optimization framework that determines the most economical operating condition of a power network while satisfying both equality constraints (power balance equations) and inequality constraints (generator limits, voltage limits, and line flow limits). The proposed formulation combined economic dispatch with system security considerations, enabling a systematic approach to minimize generation cost while ensuring secure system operation. This pioneering work became the basis for further development of AC Optimal Power Flow models and is widely referenced in power system research.

Relevance to current Research

The proposed formulation by Carpentier forms the theoretical foundation of the current project. The same OPF mathematical structure is implemented in MATLAB/MATPOWER for the IEEE 5-bus system. The objective function and system constraints used for dateset generation in this project are derived from this basic OPF formulation, making it essential for modeling and simulation.

Momoh, El-Hawary, and Adapa [2] proposed a detailed approach for solving the AC Optimal Power Flow (AC-OPF) problem by considering both active and reactive power in power transmission networks. The authors focused on the nonlinear nature of AC power flow equations and incorporated practical operating constraints such as generator real and reactive power limits, bus voltage magnitude limits, and transmission line thermal limits. The study evaluated several numerical optimization techniques, including gradient-based methods and interior point methods, to solve the OPF problem efficiently. However, the authors also highlighted that these traditional methods suffer from high computational complexity and may face convergence issues when applied to large-scale or real-time power system operations.

Relevance to current Research

This work is directly relevant to the current study as it defines the AC-OPF model used in the IEEE 5-bus system simulation. The system constraints and power flow equations proposed in this research are implemented using MATLAB/MATPOWER to generate accurate operational datasets. These datasets are then used for training the machine learning model, ensuring realistic system behavior representation.

Bertsimas et al. [3] proposed a data-driven optimization framework that integrates machine learning techniques with classical optimization problems. The authors demonstrated that complex optimization problems can be efficiently approximated using historical data instead of solving mathematical formulations repeatedly. Their approach focused on learning the mapping between input system parameters and optimal decision variables, enabling fast prediction of near-optimal solutions. This method significantly reduces computational time and is especially beneficial in real-time decision-making environments where traditional optimization techniques are too slow.

Relevance to current Research

The proposed data-driven framework is highly relevant to the present study. In this project, the same principle is applied where machine learning models are trained using MAT POWER-generated OPF solutions of the IEEE 5-bus system. The trained model learns the relationship between load conditions and optimal generation outputs, enabling fast prediction of AC-OPF solutions without repeatedly solving the optimization problem.

Zhang et al. [4] proposed an artificial neural network-based approach for solving the Optimal Power Flow problem using standard IEEE test systems such as IEEE 14-bus and IEEE 30-bus networks. The authors generated datasets using conventional OPF solvers and trained neural networks to predict optimal generator outputs, voltage magnitudes, and system cost. The study demonstrated that neural networks are capable of capturing complex nonlinear relationships in power systems and can provide near-optimal solutions with significantly reduced computation time compared to traditional iterative optimization methods. The results confirmed that machine learning techniques are suitable for real-time power system applications.

Relevance to current Research This work is closely related to the current project as it demonstrates the effectiveness of neural networks in solving OPF problems. The present study adopts a similar methodology, where the IEEE 5-bus system is used to generate training data using MATPOWER, and a machine learning model is trained to predict optimal power flow solutions efficiently.

Zimmerman et al. [5] proposed MATPOWER, a MATLAB-based open-source software package used for power flow and optimal power flow analysis in electric power systems. The authors developed MATPOWER to provide an efficient computational tool for solving AC and DC power flow problems using optimization techniques. It allows simulation of standard IEEE test systems under different loading conditions and provides results such as generation cost, voltage profile, and line flows. MATPOWER is widely used in academic research due to its simplicity, reliability, and compatibility with MATLAB, making it suitable for optimization and machine learning applications in power systems.

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Relevance to current Research

This work is directly used in the present study. MATPOWER is applied to simulate the IEEE 5-bus system and generate OPF datasets under different load conditions. These datasets are used to train the machine learning model for predicting optimal power flow solutions efficiently.

No.	Paper Title	Author Name	Key Points	Remark
1 .	Optimal Power Flow Formulation	Mr.J. Carpentier	Proposed the basic formulation of Optimal Power Flow problem to minimize generation cost while satisfying power balance and system constraints in power networks.	This work forms the fundamental base for all OPF studies and is used in this project for defining objective function and constraints.
2.	AC Optimal Power Flow in Power Systems	El-Hawary, Momoh, Adapa	Proposed AC-OPF formulation considering both active and reactive power with practical constraints such as voltage limits, line flow limits, and generator limits. Highlighted the high computational complexity of nonlinear OPF solutions.	This work is used in this project for AC-OPF modeling in IEEE 5-bussystem and MATPOWER simulations to generate realistic training data.
3.	Data-Driven Optimization Methods	Mr.Bertsimas et al.	Proposed data-driven optimization approach using machine learning techniques to approximate solutions of complex optimization problems. Focused on learning input–output mapping to reduce computational effort.	This work supports the machine learning approach used in this project to predict OPF solutions quickly instead of solving repeatedly using traditional methods.
4.	Neural Network Based OPF Solution Environment for Cloud Computing	Mr. Zhang et al.	Proposed artificial neural network approach for solving Optimal Power Flow using IEEE test systems. The model predicts generator outputs and voltage profiles based on load conditions, reducing computation time compared to traditional methods.	This work is relevant as it supports the machine learning approach used in this project for predicting OPF results in IEEE 5-bus system efficiently.
5.	Providing Security and MATPOWER Software for Power System Analysis	Mr. Zimmerman et al.	Proposed MATPOWER, a MATLAB-based tool for power flow and optimal power flow analysis. It supports AC/DC power flow, OPF studies, and simulation of IEEE test systems under different operating conditions.	This tool is used in this project to generate IEEE 5-bus system datasets for training the machine learning model and analyzing OPF results.

In summary, this project is based on research in power system optimization and machine learning techniques. Traditional AC Optimal Power Flow methods are accurate but computationally intensive and time-consuming. This work uses a machine learning approach on the IEEE 5-bus system to improve the speed and efficiency of solving the OPF problem.The proposed method learns from datasets generated using MATLAB/MATPOWER and predicts optimal operating conditions without repeated complex calculations. This reduces computational effort and improves overall system performance.The results demonstrate that the proposed approach significantly reduces computation time while maintaining acceptable accuracy. Hence, it is suitable for real-time applications in modern smart grids. Additionally, the method enhances the ability of power systems to operate efficiently under varying load conditions, making it a reliable and effective solution for future power system operations.

III. METHODOLOGY OF PROPOSED SURVEY

Data Generation using MATPOWER:

MATPOWER is used as a simulation tool to generate datasets required for solving the AC Optimal Power Flow (AC-OPF) problem. The IEEE 5-bus test system is modeled in MATLAB/MATPOWER, where multiple load conditions are

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applied to simulate different operating scenarios. For each scenario, MATPOWER computes optimal generation cost, voltage magnitudes, and power flow values while satisfying system constraints. These simulation results are stored as datasets, which serve as input for training the machine learning model.

AC Optimal Power Flow Formulation:
The AC-OPF problem is formulated to minimize the generation cost while satisfying equality and inequality constraints such as power balance equations, generator limits, voltage limits, and transmission line limits. The nonlinear nature of AC-OPF makes it computationally complex when solved using conventional optimization methods. MATPOWER solves this problem using numerical techniques, and the obtained results are considered as optimal reference solutions for training purposes.

Feature Selection and Data Preparation:
The generated data set consists of input features such as load demand (real and reactive power) and output variables such as generator power, voltage profiles, and system cost. The data is prepossessed to remove inconsistencies and normalize values for better model performance. Proper feature selection is carried out to ensure that only relevant parameters are used for training the machine learning model.

Machine Learning Model Development:
A machine learning model is developed to learn the relationship between input variables (load conditions) and output variables (optimal power flow results). The model is trained using the data set generated from MATPOWER simulations. Various regression techniques or neural networks can be used to capture the nonlinear relationship between inputs and outputs. The trained model is then capable of predicting OPF solutions without solving complex equations repeatedly.

Model Training and Testing:
The data set is divided into training and testing sets. The training data set is used to train the machine learning model, while the testing data set is used to evaluate its performance. The accuracy of the model is measured by comparing predicted outputs with actual MATPOWER results. Performance metrics such as error rate and prediction accuracy are used to validate the model.

Prediction of OPF Solutions:
Once trained, the machine learning model is used to predict optimal power flow solutions for new load conditions. The model provides outputs such as generator settings, voltage levels, and system cost in a significantly reduced time compared to conventional OPF methods. This makes the approach suitable for real-time applications.

Performance Analysis:
The performance of the proposed method is analyzed by comparing computation time and accuracy with traditional OPF solutions. The results show that the machine learning approach reduces computational complexity while maintaining acceptable accuracy. This demonstrates the effectiveness of the proposed system for modern smart grid applications.

IV. CONCLUSION AND FUTURE WORK

In this project, a machine learning–based approach is proposed to solve the AC Optimal Power Flow (AC-OPF) problem using the IEEE 5-bus system in MATLAB/MATPOWER. Datasets are generated under different load conditions, and the model is trained to learn the relationship between inputs and optimal outputs, reducing the need for repeated complex computations.The results indicate that the proposed method reduces computation time while maintaining acceptable accuracy compared to conventional OPF techniques. This makes the approach efficient and suitable for real-time power system applications and smart grid operations.

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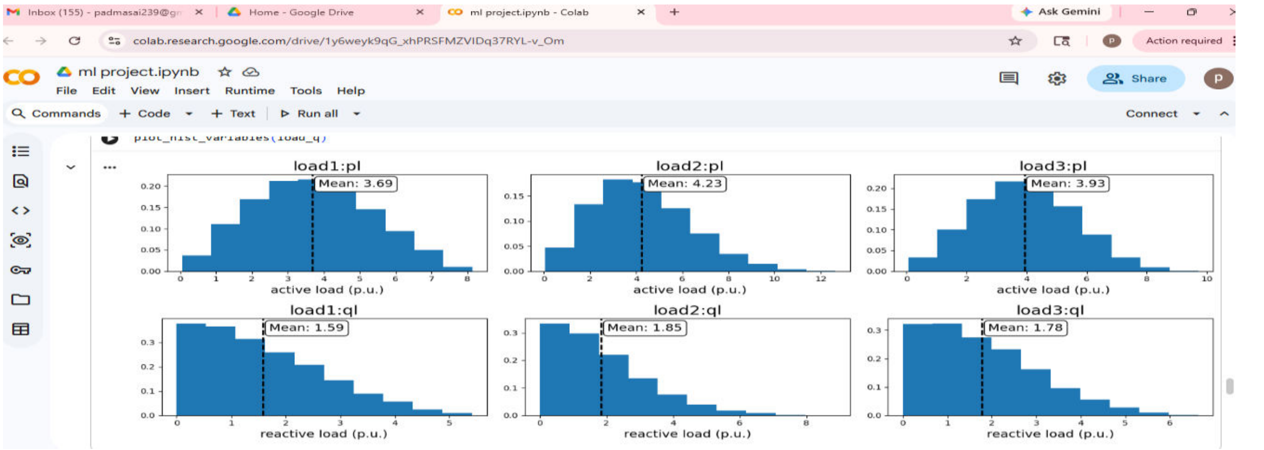

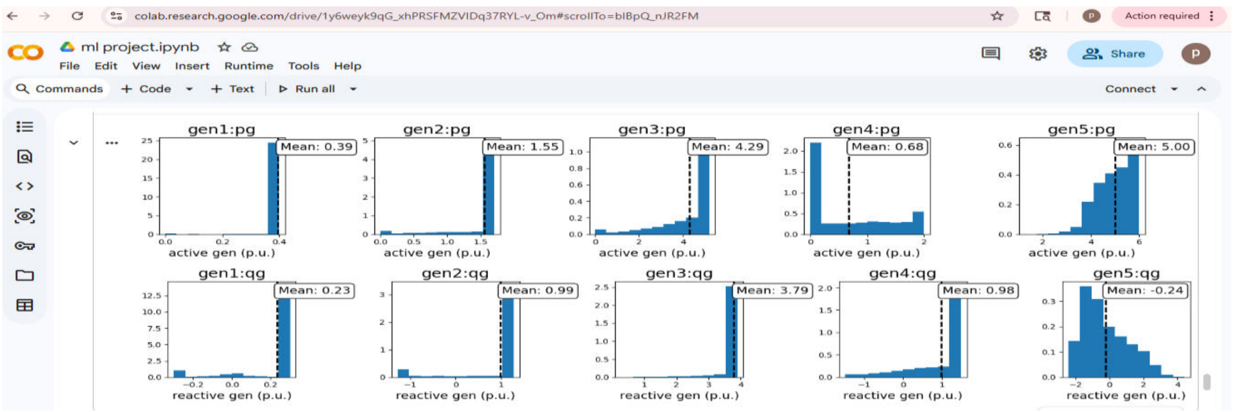

The proposed work can be further extended by applying the developed machine learning model to larger and more complex IEEE test systems such as 14-bus, 30-bus, and 57-bus systems to evaluate its scalability and performance. This will help in understanding how the model behaves under more realistic and practical power system conditions.Further improvements can be made by implementing advanced machine learning techniques such as deep learning and ensemble methods to enhance prediction accuracy and robustness. The model can also be trained using a larger and more diverse dataset to improve its generalization capability.In addition, the integration of real-time power system data can be explored to make the model more practical for real-world applications. Future work can also focus on incorporating renewable energy sources and handling uncertainties in load demand to improve system reliability and efficiency.

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