

# AI Techniques for Voltage Stability Analysis in Smart Micro Grid Systems

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**Abstract:** *The rapid growth of renewable energy integration and the increasing complexity of modern power systems have made maintaining voltage stability in smart microgrids a critical and challenging task. Voltage instability can lead to significant operational issues, equipment damage, and power outages, which necessitates the development of advanced monitoring and predictive tools capable of providing timely insights for effective decision-making. In this context, the proposed paper presents an artificial intelligence– based framework for comprehensive voltage stability assessment of smart microgrids, combining the strengths of detailed simulation models and data- driven machine learning analysis. The paper begins by designing a complete smart microgrid model in MATLAB Simulink, encompassing renewable energy sources, storage units, loads, and transmission lines, to simulate a wide range of operating scenarios including normal, stressed, and fault conditions. The simulation outputs, such as bus voltages, line currents, power flows, and frequency values, are systematically processed, cleaned, and organized to extract meaningful features that capture the dynamic behaviour of the system. These processed datasets are then used to train an SVM machine learning model, which is capable of accurately classifying the voltage stability of the microgrid into stable or unstable states, while simultaneously identifying the components most vulnerable to instability. By integrating advanced simulation and machine learning this paper aims to deliver a robust, intelligent solution that enhances the reliability, resilience, and operational efficiency of smart microgrids, ultimately enabling proactive management and improved system performance under diverse operating conditions.*

**Keywords:** - MATLAB, SVM, Machine Learning.

## I. INTRODUCTION

The growing demand for reliable, efficient, and sustainable energy has led to the increasing deployment of smart microgrids, which integrate renewable energy sources such as solar and wind, along with storage systems and conventional loads. Unlike traditional power systems, smart microgrids operate in a more dynamic and decentralized manner, where fluctuations in generation and load can significantly impact system stability, particularly voltage stability. Voltage instability can manifest as voltage dips, rapid fluctuations, or even system collapse, posing serious risks to power quality, equipment safety, and overall operational reliability. Ensuring continuous voltage stability in such a complex and interconnected system requires advanced monitoring tools capable of analysis a large volume of simulated data. Traditional analytical methods, while useful, often fall short in handling the nonlinearities and uncertainties inherent in modern microgrid operations, highlighting the need for intelligent, data-driven approaches that can predict, assess, and manage voltage stability effectively.

In this paper, we propose an artificial intelligence– based framework for voltage stability assessment in smart microgrids that combines high-fidelity simulation with predictive machine learning techniques. A comprehensive microgrid model is developed in MATLAB Simulink, incorporating renewable generation units, energy storage systems, loads, and transmission lines, to simulate a variety of operating conditions including normal, stressed, and fault scenarios. The simulation outputs, such as voltages, currents, power flows, and frequency variations, are



systematically processed, organized, and enriched through feature engineering to capture critical indicators of system performance. These datasets are then used to train an SVM machine learning model, which can accurately classify the voltage stability of the system and identify components most affected by instability. By integrating simulation, AI model, this paper aims to provide a robust, transparent, and user-friendly solution that supports proactive decision-making, improves system reliability, and enhances the operational efficiency of smart microgrids under a wide range of conditions.

## II. LITERATURE REVIEW

1] Fathollahi, et al. This review explores the important role of artificial intelligence and machine learning approaches in managing the developing stability characteristics of smart grids. This work starts with a discussion of the smart grid's dynamic structures and subsequently transitions into an overview of machine learning approaches that explore various algorithms and their applications to enhance smart grid operations. A comprehensive analysis of frameworks illustrates how machine learning and artificial intelligence solve issues related to distributed energy supplies, load management and contingency planning. This review includes general pseudocode and schematic architectures of artificial intelligence and machine learning methods which are categorized into supervised, semi-supervised, unsupervised and reinforcement learning. It includes support vector machines, decision trees, artificial neural networks, extreme learning machines and probabilistic graphical models, as well as reinforcement strategies like dynamic programming, Monte Carlo methods, temporal difference learning and Deep Q-networks, etc. Examination extends to stability, voltage and frequency regulation along with fault detection methods that highlight their applications in increasing smart grid operational boundaries. The review underlines the various arrays of machine learning algorithms that emphasize the integration of reinforcement learning as a pivotal enhancement in intelligent decision-making within smart grid environments. As a resource this review offers insights for researchers, practitioners and policymakers by providing a roadmap for leveraging intelligent technologies in smart grid control and stability analysis.

2] Alaerjan, Alaa, et al. In this paper, the author proposes a symmetric approach to enhance SG stability by integrating various machine learning (ML) and deep learning (DL) algorithms, where symmetry is observed in the balanced application of these diverse computational techniques to predict and ensure the grid's stability. These algorithms utilized a dataset containing the simulation results of the SG stability. The learning phase of these algorithms is based on imprecise and unreliable data. To overcome this limitation, the fusion of classifiers can be a powerful approach to models inaccurate and uncertain data, providing more robust and reliable predictions than individual classifiers. Voting and Dempster-Shafer (DS) methods, two commonly used techniques in ensemble learning, were employed and compared. The results show that the use of the fusion of distinct classifiers with voting theory achieves an accuracy of 99.8% and outperforms several other methods including the DS method.

3] Liu, Wentao, et al. This article reviews four types of classic grid stability assessment methods based on AI in the recent literature first, where different AI algorithms from the literature are summarized and compared. Moreover, as the number of power converters using grid forming control intensively increases in the modern system, the influence of the converter parameters on grid stability needs to be investigated. In this context, the concept of the converter-dominated power system state of stability (CDPS-SOS) assessment based on AI is qualitatively discussed. The CDPS-SOS assessment can reveal the system stability margin by considering the converter control parameters and grid bus voltages.

4] Nair, Divya R., et al. The proposed controller considers various uncertainties caused by load variations, state of charge of the battery of microgrids, and power tariff based on the availability of power in microgrids. This paper presents a detailed analysis of the integration of wind and solar microgrids with the grid for dynamic power flow management in order to improve the power quality and to reduce the burden, thereby strengthening the central grid. A smart grid system with multiple smart microgrids coupled with a renewable energy source with tariff control and judicious power flow management was simulated for power-sharing and power quality improvement. A hardware prototype of the artificial intelligence-based  $I \cos\phi$  control algorithm with nonlinear load was also implemented



successfully. Furthermore, the economic viability was investigated to ensure the feasibility of the smart microgrid system with the proposed controller design for power flow management and power quality improvement.

5] Mossie, Molla Addisu, et al. This study addresses voltage stability assessment in power systems using machine learning (ML) to overcome the computational limitations of traditional methods. By employing Linear Regression (LR), Random Forest (RF), Gradient Boosting (GB), and Support Vector Machine (SVM), we predict Fast Voltage Stability Indices (FVSI) at nominal load as well as under varying loads (10–150%) in 15 kV Ethiopian distribution networks: a 35-bus Bata feeder system and a 53-bus Papyrus feeder system. RF and GB models achieved superior accuracy with  $R^2$  values of 0.999 and 0.9998 respectively, significantly outperforming LR and SVM which exhibited substantial deviations. The GB model achieves the highest accuracy, with RMSE values of 0.0002 (53-bus) and  $2.419e-05$  (35-bus), while RF yields RMSE values of 0.0039 (53-bus) and 0.00120 (35-bus), demonstrating strong predictive performance. The FVSI threshold analysis revealed critical stability limits, with values approaching 1.0 indicating proximity to voltage collapse. The analysis identified buses 36, 32, and 21 in the 53-bus system (FVSI values: 0.087, 0.082, and 0.080) and buses 27 and 16 in the 35-bus system (FVSI values: 0.085 and 0.082) as critical instability risk points requiring immediate monitoring. These findings underscore the efficacy of ensemble methods for rapid voltage stability assessment and emphasize the need for targeted interventions in high-risk areas to bolster grid resilience in Ethiopian distribution networks.

6] Mohammadi, Ebrahim, et al. This article presents a review on different applications of AI-based techniques in microgrids such as energy management, load and generation forecasting, protection, power electronics control, and cyber security. Different AI tasks such as regression and classification in microgrids are discussed using methods including machine learning, artificial neural networks, fuzzy logic, support vector machines, etc. The advantages, limitations, and future trends of AI applications in microgrids are discussed.

7] Alhamrouni, Ibrahim, et al. This review comprehensively examines the burgeoning field of intelligent techniques to enhance power systems' stability, control, and protection. As global energy demands increase and renewable energy sources become more integrated, maintaining the stability and reliability of both conventional power systems and smart grids is crucial. Traditional methods are increasingly insufficient for handling today's power grids' complex, dynamic nature. This paper discusses the adoption of advanced intelligence methods, including artificial intelligence (AI), deep learning (DL), machine learning (ML), metaheuristic optimization algorithms, and other AI techniques such as fuzzy logic, reinforcement learning, and model predictive control to address these challenges. It underscores the critical importance of power system stability and the new challenges of integrating diverse energy sources. The paper reviews various intelligent methods used in power system analysis, emphasizing their roles in predictive maintenance, fault detection, real-time control, and monitoring. It details extensive research on the capabilities of AI and ML algorithms to enhance the precision and efficiency of protection systems, showing their effectiveness in accurately identifying and resolving faults. Additionally, it explores the potential of fuzzy logic in decision-making under uncertainty, reinforcement learning for dynamic stability control, and the integration of IoT and big data analytics for real-time system monitoring and optimization.

8] You, Shutang, et al. This paper first reviewed existing literature on using artificial intelligence for power grid stability assessment. Then a machine-learning-based tool is presented and developed to assess power grid transient stability, frequency stability, and small signals stability. Test results verified the accuracy and effectiveness of the AI tool for power grid stability assessment.

9] Choudhary, Er Aman, et al. In this review, the author synthesises the application of this range of AI-driven models (machine learning, deep learning, reinforcement learning and hybrids) to key power system functions. For example, fault detection speeds of under 5ms with 98.5% accuracy have been demonstrated, using wavelet transform integrated with support vector machines, for multi terminal DC (MTDC) grids. Applying artificial neural networks (ANNs), the classification accuracy was 97.8% and localization error was below 5%. CNNs, using deep learning based on CNNs, also went beyond 99% accuracy in the fault diagnosis of underground cables. Recurrent neural networks (RNNs) and long short term memory (LSTM) models improved the short-term load forecasting accuracy up to 15% and ANN- PSO



algorithms improved the V2G scheduling with minimum battery wear and peak shaving. The paper also recognizes critical research gaps (e.g., explainability, data privacy, edge deployment, cybersecurity) that need to be addressed for robust and impactful deployment of ML. Integrating these intelligent systems into power networks allows utilities to move closer to that of resilient, efficient and sustainable energy infrastructures.

10] Anonto, Hasanur Zaman, et al. The study at hand suggests dedicating a new type of energy management of the microgrid by using the machine-learning algorithms, namely the Random Forest (RF) regressor along with real-time forecasting the energy use and renewable-energy production. Integrating grid-stability measures, that is, voltage and frequency variation into the predictive model, the framework enhances the accuracy of the energy dispatch and storage plans. The ability of the system to coordinate energy movement as an additional storage system that stores when there is surplus and releases when shortage occurs encourages grid stability with the reduced dependence on the main grid.

11] Abbass, Muhammad Jamshed, et al. The present investigation in this paper involves the utilization of an artificial intelligence network (ANN) to facilitate the training and prediction of the nodal voltage level pertaining to the IEEE 4-bus system. Four discrete models have been postulated to authenticate the efficacy of the Artificial Neural Network (ANN) methodology. The findings indicate that the ensemble of models exhibits superior performance compared to other models in forecasting the nodal voltage stability of the aforementioned electrical system.

12] Gopalakrishnan, R., et al. proposed work focuses on enhancing the stability of the grid and improves the power quality in order to ensure consistent and uninterrupted supply of electricity. Hence, AI based methodologies are incorporated in the present research, where the proposed system integrates HRES (Hybrid RES) such as PV systems, WT (Wind Turbine) and battery storage system. Moreover, in order to obtain better input from these sources, proposed system opts for fuzzy based MPPT (Maximum Power Point Tracking) approach for PV, P&O (Perturb and Observe) based MPPT approach for WT and PI (Proportional-Integral) controller is used for battery management to ensure optimal operation under varying conditions. Subsequently, the conversion of DC (Direct Current) to AC (Alternating Current) is performed and this signal is then processed using PWM (Pulse Width Modulation). However, in order to improve the performance of PWM, proposed work focuses on optimizing the performance of PWM using hybrid APOPSO (Artificial Physics Optimization- Particle Swarm Optimization) in ANN controller.

13] Pandey, Amit Kumar, et al. This paper presents a novel AI-based Adaptive Power Optimization with Learning for Load Operations (APOLLO) Algorithm for improving power quality in DC microgrid systems, which significantly outperforms conventional control methods. Our hybrid framework integrates Convolutional Neural Networks (CNNs) for feature extraction, Long Short-Term Memory (LSTM) networks for temporal pattern recognition, and Deep Reinforcement Learning (DRL) for adaptive control optimization. The proposed system demonstrates superior voltage regulation, achieving a 94.7% reduction in steady-state error and a 78.3% faster transient response compared to traditional PI controllers.

14] Thamilmaran, Alwar, et al. The incorporation of artificial intelligence techniques for the control of MG has been gaining attention for the past decade to enhance its functionality and operation. This paper presents a critical review of various artificial intelligence (AI) techniques that have been implemented for the hierarchical control of MGs and their significance, along with the basic control strategy.

15] Zahid, Mahnoor, et al. This review investigates the emerging role of artificial intelligence (AI) as a powerful tool for optimizing PQ in MG. It presents a detailed overview of various AI-based methods, including machine learning (ML), metaheuristics, deep learning, fuzzy logic, and hybrid approaches and their implementation in areas like harmonic suppression, voltage and frequency regulation, islanding detection, renewable energy coordination, and predictive diagnostics. The study evaluates these techniques based on key performance indicators, such as precision, scalability, and suitability for real-time operation, while also addressing challenges related to data reliability, interpretability, and cybersecurity.



**III. METHODOLOGY**

The proposed system for “Artificial Intelligence Based Voltage Stability Assessment of Smart Micro Grid” works by using Artificial Intelligence to check whether the voltage of a smart microgrid is stable or unstable. First, a smart microgrid model is created in MATLAB/Simulink which includes solar panels, battery storage system, diesel generators, transmission lines, and electrical loads. Voltage sensors are connected at 14 different buses to continuously measure voltage values. Different conditions such as sudden load increase, solar power fluctuation, generator failure, and fault conditions are created in the simulation to collect voltage data. After collecting the data, important values like voltage level, voltage variation, minimum voltage, maximum voltage, and average voltage are calculated. These values are given to an Artificial Intelligence technique called Support Vector Machine (SVM) for training. The SVM model learns the difference between stable and unstable conditions of the microgrid. After training, the AI system continuously checks new voltage readings and quickly predicts whether the system is stable or unstable. If any instability is detected, the system gives an early warning so that corrective actions such as battery support, generator control, or load reduction can be taken to avoid voltage collapse and power failure. Thus, the proposed system helps in improving power quality, reliability, and safe operation of the smart microgrid.

**BLOCK DIAGRAM**

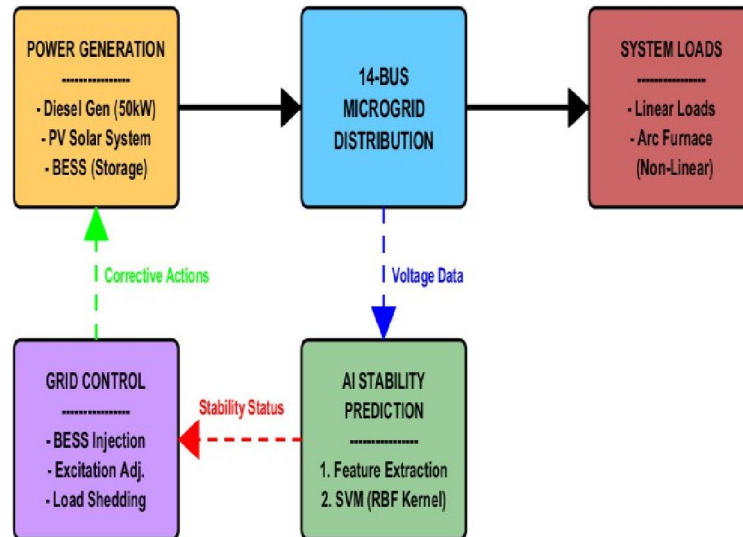


Fig. 1 Shows the Block Diagram of the System



**SYSTEM ARCHITECTURE DIAGRAM**

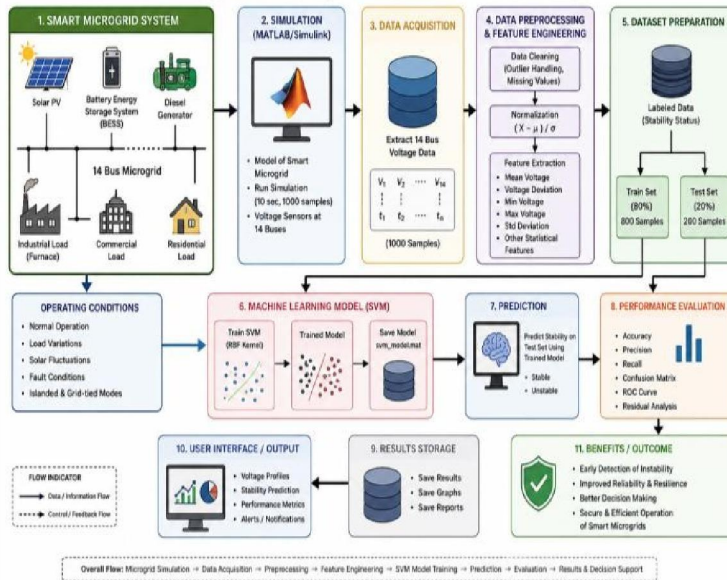


Fig. 2 shows the system architecture diagram of the system

**FLOW CHART**

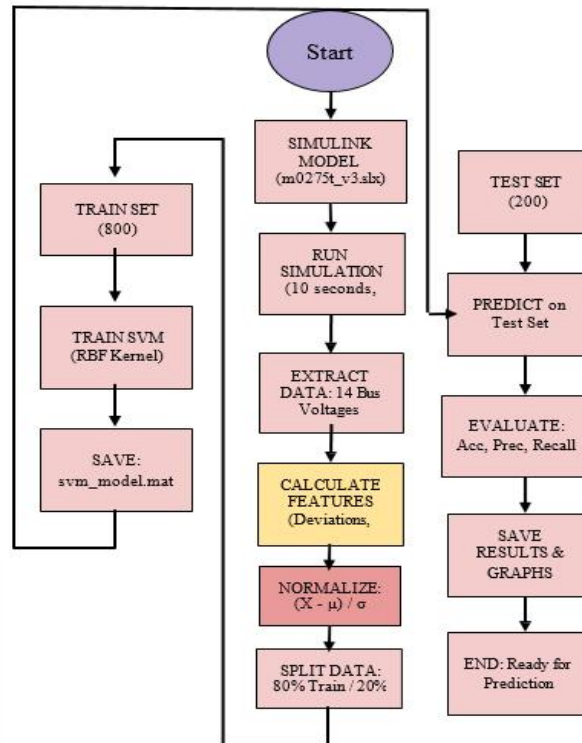


Fig. 3 shows the flow chart of the system



**WORKING**

The working of this system begins with the development of a smart microgrid model in MATLAB/Simulink, where different electrical and renewable energy components such as solar photovoltaic (PV) systems, battery energy storage systems (BESS), diesel generators, transformers, transmission lines, buses, and dynamic electrical loads are interconnected to form a complete microgrid network. Voltage sensors are placed at multiple buses to continuously monitor the voltage levels of the system under different operating conditions. The simulation is carried out for various scenarios such as sudden load increase, renewable energy fluctuation, generator disturbances, and fault conditions to observe the behaviour of the microgrid during stable and unstable situations. During simulation, important electrical parameters such as bus voltage, current, power flow, and frequency variations are collected and stored as datasets for further analysis.

After collecting the simulation data, preprocessing and feature extraction techniques are applied to obtain important voltage stability parameters such as voltage deviation, average voltage, minimum voltage, maximum voltage, and stability margin. These extracted features represent the operating condition of the microgrid and are used as input to the Artificial Intelligence-based Support Vector Machine (SVM) model. The SVM algorithm is trained using historical simulation data to learn the difference between stable and unstable operating conditions of the smart microgrid. Once the training process is completed, the developed AI model continuously analysis new voltage data and predicts the stability condition of the system in real time with high accuracy. If abnormal voltage fluctuations or unstable conditions are detected, the system generates an early warning indication so that corrective actions such as battery support activation, load reduction, generator control, or voltage regulation can be implemented to prevent voltage collapse and maintain reliable operation of the smart microgrid. Thus, the proposed system provides intelligent voltage stability monitoring, improves power quality, enhances operational reliability, and supports efficient management of modern smart microgrid systems.

**IV. SYSTEM REQUIREMENT SOFTWARE REQUIREMENT**

**1. MATLAB Software**

**V. IMPLEMENTATION AND RESULT IMPLEMENTATION**

Step 1: Development of Smart Microgrid Model in MATLAB/Simulink

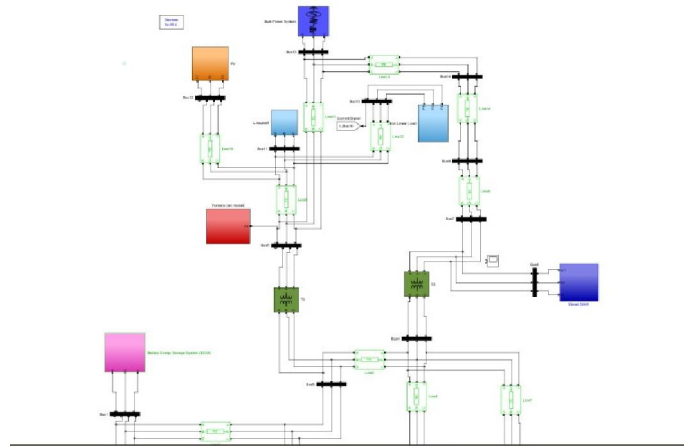


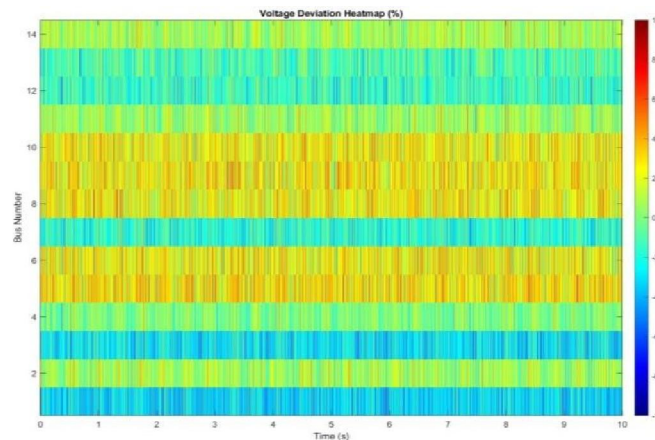
Fig. 4 shows smart microgrid model developed in MATLAB/Simulink for voltage stability assessment



The above figure shows the implementation of the smart microgrid system developed in MATLAB/Simulink for voltage stability assessment. The model consists of different components such as a photovoltaic (PV) system, Battery Energy Storage System (BESS), diesel generator, transmission lines, buses, transformers, and dynamic loads connected together to form a smart microgrid network. Multiple buses and transmission lines are used to distribute electrical power across the system, while voltage measurements are taken from different points of the network. The furnace load is included to create sudden load variations and voltage fluctuations in the microgrid. This complete Simulink model is used to simulate different operating conditions such as renewable power variation, load disturbances, and fault situations. The generated voltage data from this model is later used for training and testing the Artificial Intelligence-based Support Vector Machine (SVM) model for voltage stability prediction.

### RESULT

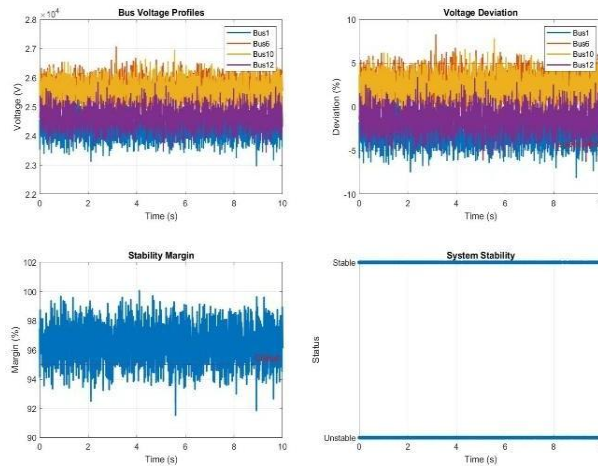
The results demonstrate that the proposed AI-based voltage stability assessment system effectively maintains stable operation of the smart microgrid under different operating conditions. The bus voltage profiles remain close to nominal values with only minor fluctuations within acceptable limits, confirming effective voltage regulation and disturbance handling capability. Statistical analysis shows that most operating conditions maintain adequate stability margins, while only a few cases exhibit temporary instability. Furthermore, the machine learning model achieves high accuracy and strong classification performance with minimal prediction errors, validating the reliability of the AI-based approach for real-time voltage stability monitoring and intelligent decision support in smart microgrids.



**Fig. 5 Voltage deviation heatmap showing voltage variation across different buses with time**

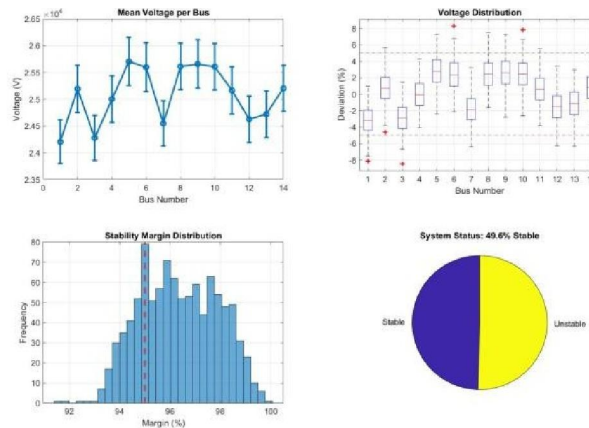
The above figure shows the voltage deviation heatmap obtained from the smart microgrid simulation. The graph represents voltage variation at different buses over a simulation period of 10 seconds. The horizontal axis represents time, while the vertical axis represents the bus numbers of the microgrid system. Different colours indicate the level of voltage deviation in percentage. Blue shades represent lower voltage values, green shades indicate normal operating conditions, and yellow to red shades represent higher voltage deviations or unstable conditions. From the heatmap, it can be observed that some buses experience higher voltage fluctuations due to varying load conditions and renewable energy disturbances. This analysis helps in identifying weak buses and unstable operating regions in the microgrid. The generated voltage deviation data is further used for training the SVM-based Artificial Intelligence model for accurate voltage stability prediction.





**Fig. 6 Analysis of bus voltage profiles, voltage deviation, stability margin, and system stability status**

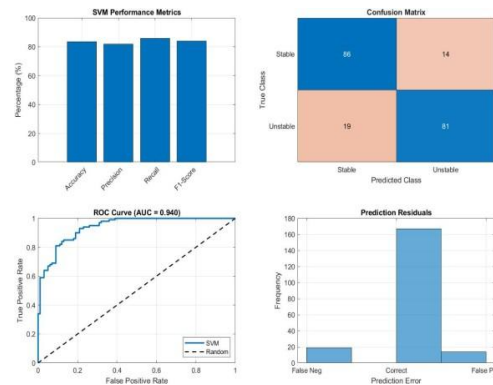
The above figure shows the overall voltage stability analysis of the smart microgrid system under different operating conditions. The first graph represents the voltage profiles of different buses with respect to time, showing voltage fluctuations occurring in the microgrid. The second graph illustrates the voltage deviation percentage for selected buses, where the variations remain mostly within the acceptable operating limit. The third graph shows the stability margin of the system, indicating that the microgrid operates close to the stable region during the simulation period. The final graph represents the overall system stability status, where the Artificial Intelligence-based SVM model classifies the operating condition as stable or unstable. From the obtained results, it can be observed that the proposed system effectively monitors voltage variations and helps in identifying stability conditions of the smart microgrid in real time.



**Fig. 7 Statistical analysis of bus voltage, voltage deviation, stability margin, and system stability condition**

The above figure shows the statistical analysis results of the smart microgrid voltage stability assessment system. The first graph represents the mean voltage value of each bus along with voltage variation limits, indicating the voltage performance of different buses in the microgrid. The second graph shows the voltage deviation distribution using box plots, where the spread of voltage variation for each bus can be observed clearly. The third graph illustrates the stability margin distribution of the system, showing that most operating conditions remain within the stable region above the critical margin level. The final pie chart represents the overall system stability condition, indicating the percentage of stable and unstable operating states obtained during simulation. These results demonstrate that the proposed AI-based system can effectively analysis voltage behaviour and identify stability conditions of the smart microgrid under varying operating scenarios.





**Fig. 8 Performance analysis of the SVM model using accuracy metrics, confusion matrix, ROC curve, and prediction residuals**

The above figure shows the performance evaluation results of the proposed Support Vector Machine (SVM) model used for voltage stability prediction in the smart microgrid system. The first graph represents important performance metrics such as accuracy, precision, recall, and F1-score, indicating that the SVM model achieves high prediction performance. The confusion matrix shown in the second graph illustrates the number of correctly and incorrectly classified stable and unstable conditions. The third graph presents the ROC curve with a high Area Under Curve (AUC) value, which demonstrates the strong classification capability of the proposed model. The final graph shows the prediction residual analysis, indicating the number of correct predictions along with false positive and false negative predictions. From these results, it is observed that the proposed AI-based SVM model can effectively identify voltage stability conditions with high reliability and accuracy in real-time smart microgrid applications.

## VI. CONCLUSION

The “Artificial Intelligence Based Voltage Stability Assessment of Smart Microgrid” paper presents an intelligent and efficient approach for monitoring the voltage stability of a smart microgrid system using Artificial Intelligence techniques. In this work, a smart microgrid model was developed in MATLAB/Simulink by integrating renewable energy sources, storage systems, transmission lines, and electrical loads. The collected voltage data was processed and analysis using the Support Vector Machine (SVM) algorithm to identify stable and unstable operating conditions of the microgrid. The system helps in continuous voltage monitoring and supports early detection of instability caused by load variation, renewable energy fluctuation, and fault conditions. The proposed approach improves the reliability, stability, and operational performance of the smart microgrid and demonstrates the importance of AI-based techniques in modern power system monitoring and control.

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