Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Navigating Modern Power Systems: A Survey Of Recent Advancements In Voltage Stability Analysis And Optimization Techniques

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The evolution of the electric power industry towards renewable energy sources, electric vehicles, and advanced power electronics has necessitated a reevaluation of voltage stability and optimization techniques. This literature review examines recent advancements in voltage stability analysis and optimization methodologies, considering the challenges posed by fluctuating renewable energy sources and nonlinear loads. The objectives are to synthesize recent research findings, identify gaps, and explore implications for industry and academia. By focusing on deep learning, renewable energy integration, advanced control devices, and electric vehicle charging, the review offers a comprehensive overview of contemporary voltage stability analysis. Additionally, optimization techniques such as the Grey Wolf algorithm are explored, highlighting their role in enhancing power system performance. Through this review, insights are provided to guide future research, inform industry practices, and shape policy decisions towards resilient, efficient, and sustainable power systems

Keywords: Voltage Stability, Power System Stability, Voltage profile, stability analysis, optimization techniques, Grey Wolf algorithm, optimal power flow

INTRODUCTION

‘The electric power industry has witnessed a paradigm shift with the advent of renewable energy sources, electric vehicles, and advanced power electronics, necessitating a critical analysis of voltage stability and optimization techniques. Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition’[1][2]. Historically, voltage stability has been a cornerstone of power system design and operation, ensuring the reliability and quality of electricity supplied to consumers. ‘In recent years, the integration of fluctuating renewable energy sources and nonlinear loads has exacerbated voltage stability challenges,

underscoring its significance in the context of modern power systems and the transition to sustainable energy'[3].
As we narrow down, this review focuses on the recent advancements in voltage stability analysis. 'The surge in digital technologies, such as artificial intelligence and machine learning, has opened new avenues for assessing and enhancing voltage stability'[4]. Moreover, the implementation of optimization techniques has become pivotal in refining power system operations, including fuel cost reduction, power quality enhancement, and voltage stability improvement, particularly in industrial settings where power quality is crucial for operational efficiency and equipment longevity.

OBJECTIVES

The primary objectives of this literature review are to systematically collate and synthesize the findings from recent studies on voltage stability analysis and optimization techniques, identify the prevailing research gaps, and the innovative methodologies employed to optimize power system performance and explore the implications of these studies for industry and academia.

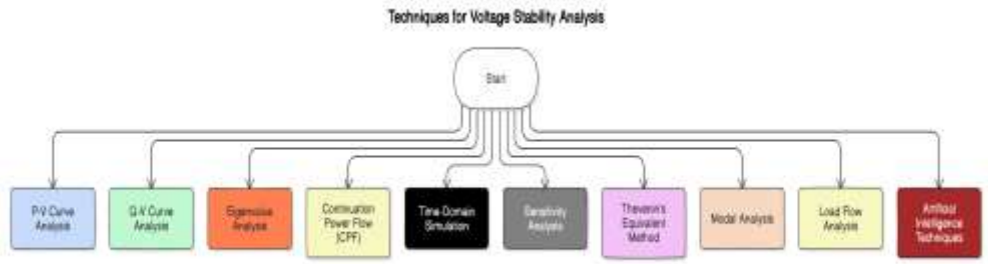
Scope

This literature review explores recent research exploring various facets of voltage stability analysis within modern power systems. It covers a wide array of topics, including deep learning methodologies, the incorporation of renewable energy systems, the utilization of advanced control devices such as FACTS, and the impact of electric vehicle charging on distribution networks. Optimization techniques are also explored, with a specific focus on one recent paper that combines rapid voltage stability assessment and the Grey Wolf algorithm to optimize fuel cost and line loadability. The scope of this review is confined to articles published in the past few years, primarily focusing on methodologies and applications that are directly relevant to voltage stability and optimization in contemporary power systems. Studies that fall outside the realms of voltage stability and do not provide insights into optimization techniques are excluded to maintain the review's focus.
The rationale for this literature review is grounded in the need to consolidate the burgeoning body of literature that has emerged in response to the increasingly complex dynamics of modern power systems. This review is necessary to bridge the knowledge gap between traditional power system stability analysis and contemporary challenges introduced by new technologies and energy sources. The relevance of this literature review extends to power system engineers, policymakers, and researchers who are at the forefront of designing resilient, efficient, and sustainable power systems.

Contribution

By delving into the recent literature, this review will elucidate the latest trends and technological innovations in voltage stability analysis and optimization techniques. 'The contribution of this survey lies in its ability to amalgamate diverse research findings, offer a critical analysis of methodologies and results, and foster an understanding of the implications for the future design and operation of power systems'[5]. The synthesis of these papers will serve as a valuable resource for guiding future research directions, informing industry practices, and influencing policy choices concerning the stability and optimization of power systems.

1. VOLTAGE STABILITY ANALYSIS



2.1 Findings

'The reviewed papers contribute to the field of voltage stability analysis in power systems, particularly considering the integration of new energy sources and the application of various technological and methodological advancements. These contributions can be grouped into three main categories'[6]: (1) Voltage Stability Indices and Prediction Models, (2) System Control and Reconfiguration Approaches, and (3) Impact of Distributed Energy Resources on the Voltage Stability(VS).

Here's a table summarizing the primary techniques used for voltage stability analysis, derived from the descriptions provided:

Technique	Overview	Objective	Usage
P-V Curve Analysis	Charts the connection between bus voltage and power load.	Pinpoints the critical nose point where voltage collapse is imminent.	Used for steady-state voltage stability assessments and system planning.
Q-V Curve Analysis	Plots voltage against reactive power introduced at a bus.	Identifies vulnerable buses where voltage instability may arise.	Analyzes the need for reactive power compensation.
Eigenvalue Analysis	Assesses system stability using the Jacobian matrix from power flow equations.	Identifies instability by detecting negative or near-zero eigenvalues.	Serves as an early indicator of instability in dynamic systems.

Continuation Power Flow	Assesses system stability using the Jacobian matrix from power flow equations.	Explores voltage stability limits and critical thresholds.	Used to forecast voltage collapse in static and dynamic contexts.
Time-Domain Simulation	Models system response to disturbances over time.	Investigates dynamic voltage fluctuations after transient events.	Crucial for assessing transient disturbances' effects on voltage stability.
Sensitivity Analysis	Calculates how system changes impact voltage.	Identifies critical points where minor changes can cause instability.	Helps in planning and operational strategies to enhance voltage reliability.
Thevenin's Equivalent Method	Uses Thevenin's equivalent impedance to assess voltage collapse proximity.	Highlights areas where instability may occur by comparing impedances.	Useful for real-time voltage stability monitoring.
Modal Analysis	Breaks down the system into modes to identify those leading to instability.	Determines which modes (eigenvalues) are vulnerable to instability.	Effective in multi-machine systems to pinpoint weak grid sections.
Load Flow Analysis	Evaluates voltage stability by assessing voltage profiles under load changes.	Ensures proper voltage levels across the grid.	Commonly used in planning and operational contexts.
Artificial Intelligence	Utilizes AI to forecast voltage stability from large datasets.	Provides real-time voltage instability assessments.	Increasingly applied in smart grid systems and complex power system evaluations.

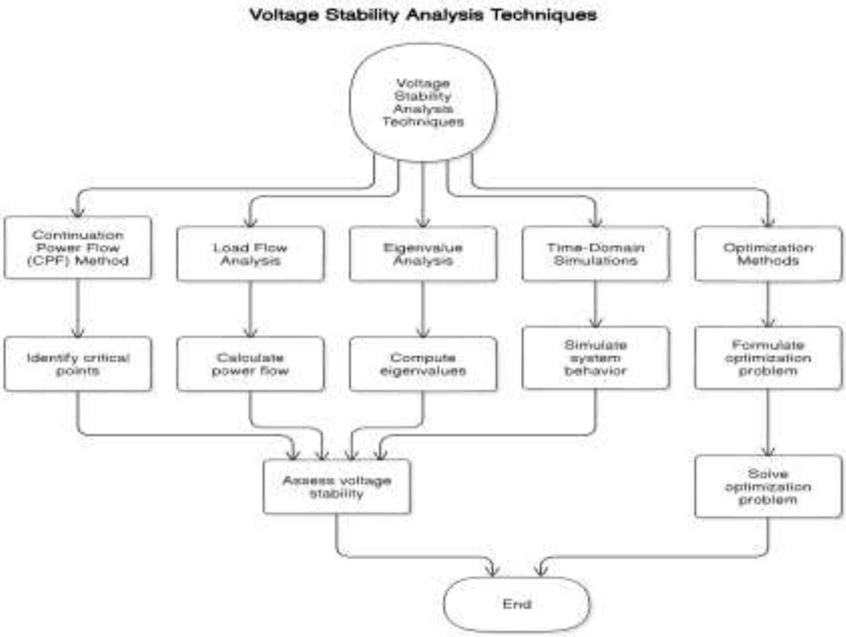
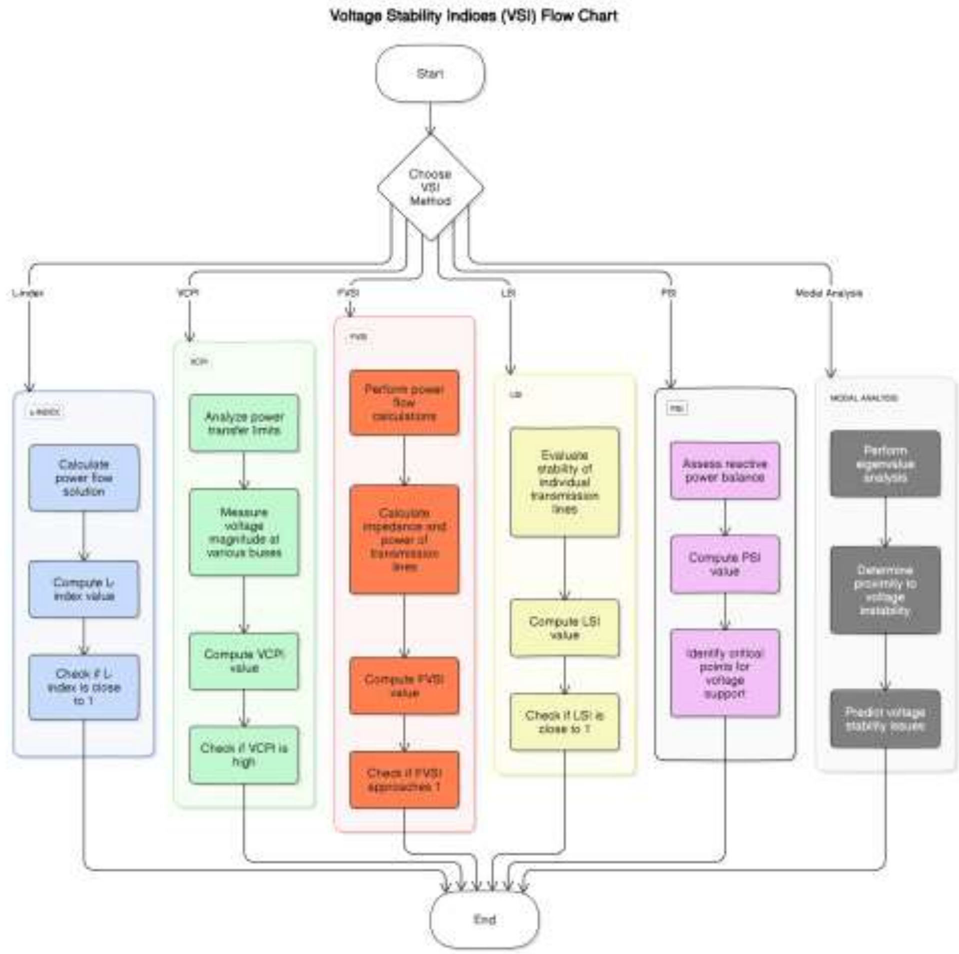


Fig.1 Voltage Stability Analysis Techniques

2.1.1 Voltage Stability Indices(VSI) and Prediction Models



A common goal of several papers is to develop and validate new voltage stability indices or to enhance existing ones, as well as to propose prediction models that can accurately anticipate voltage stability issues.

‘Li et al. [7] present a modified static voltage stability index (NVSI) that integrates stochastic wind and photovoltaic (PV) power into its computation. They develop a short-term prediction model employing the Random Forest algorithm, showcasing its efficacy in forecasting PCC voltage stability’[3][9][10]. [8] propose a Transformer-based STVSA approach to tackle the issue of class imbalance in practical scenarios. ‘By leveraging the basic Transformer architecture, they introduce a stability assessment Transformer as a classification model, reflecting the relationship between system operational states and resulting stability outcomes. [3][11] suggest ‘a novel PMU measurements-based STVSA technique utilizing deep transfer learning. This method utilizes real-time dynamic information captured by PMUs to establish an initial dataset, employing temporal ensembling for sample labeling and least squares generative adversarial networks (LSGANs) for data augmentation (DA), enabling efficient DL on small-scale datasets. Moreover, it enhances adaptability to topological changes by exploring connections between various faults'[3]. [12] examine the voltage stability of grid-tied VSG connected to a weak grid, proposing an impedance model for measuring voltage stability and identifying the interaction between VSG and the weak grid. Findings indicate that weak grid strength can induce wideband oscillation of VSG. [13] Zhang et al. introduce a load dynamic stability index (LDSI) for short-term voltage stability assessment and control[14] [15]. This index utilizes periodically identified load models to analyze the role of load dynamics during voltage dip events. [16][17] suggest an online adaptive VSA method based on data domain adaptation, enabling rapid adaptation to new topologies following changes with limited amounts of unlabelled post-change data. 'Gao [18] proposes a voltage stability index suitable for distributed generation and distribution networks, derived from the relationship between power balance, voltage balance, and the impact of wind power access location, access capacity, and faults on voltage stability'[3]. Salman [19] investigates voltage stability monitoring using voltage stability indices and Artificial Neural Networks (ANN), offering an effective and highly accurate tool for monitoring purposes.

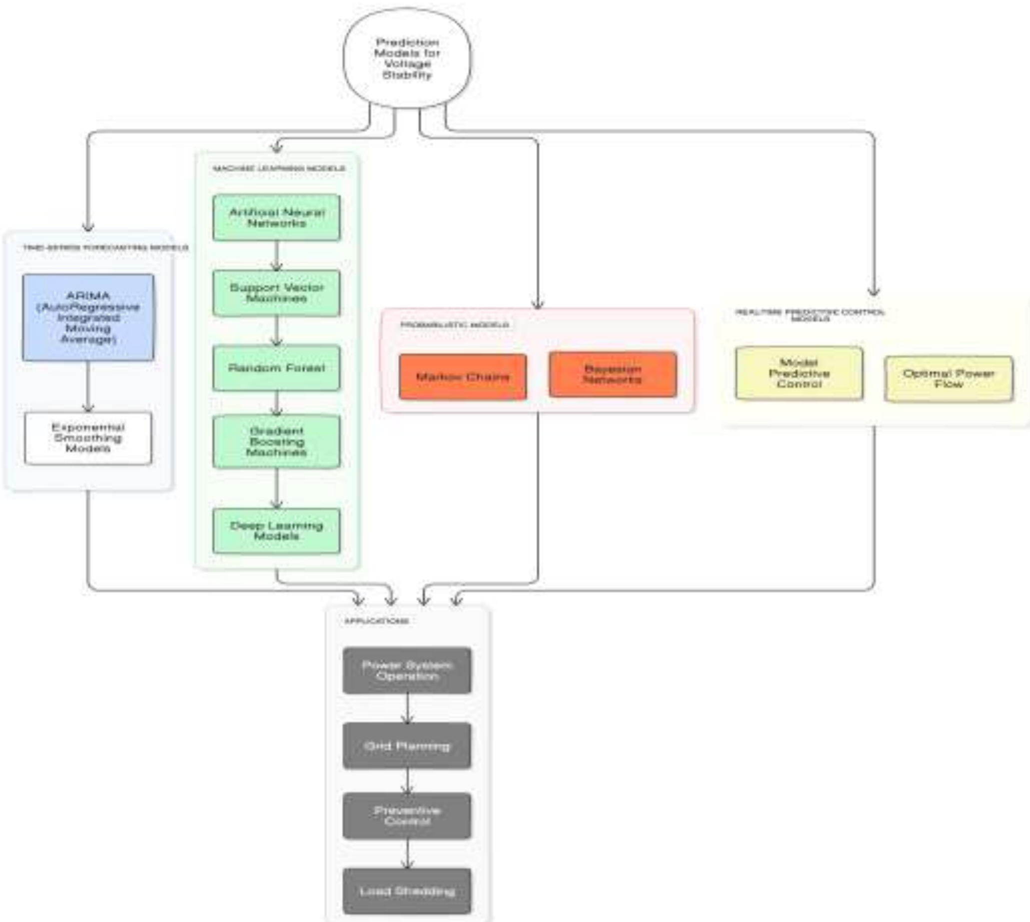


Fig.2. Voltage Stability Indices

Stanchev [20] evaluate voltage stability in microgrid-tied photovoltaic systems. They analyze voltage stability for two scenarios in a smart microgrid with PV plants connected at different nodes, using simulations in NEPLAN. The results allow evaluation of permissible PV plant connection limits for network stability. 'Guddanti et al. [21] suggest employing graph neural networks to estimate voltage stability margins while considering topology flexibilities'[3]. Tan et al. [22] introduce a refined method for evaluating the voltage stability of offshore wind farms (OWFs).
considering the cable capacitance parameters and dynamics of the converter. Tian et al. [23] examine the stability of high-voltage in small-size single crystal Ni-rich layered cathodes within sulphide-based all-solid-state lithium batteries at 4.5 V. Wang et al. [24] explore the design of interface coatings to enhance the dynamic voltage stability of solid-state batteries [25] [26].
Zhou et al. [27] propose a
The Thevenin equivalent analytical approach for assessing voltage stability in systems with wind power. They introduce an equivalent model of wind power integration and derive analytical expressions of Thevenin equivalent parameters to analyse the influence of wind power on voltage stability.
'Lei et al. [28] focus on determining the maximum wind power penetration ratio from a voltage stability perspective'[29]. 'They use the impedance modulus margin index (IMMI) and the Thevenin model to propose an analytical calculation method, which is then validated through a case study' [30].
Jia et al. [31] propose an improved power flow model that accounts for the electrothermal coupling effect in overhead transmission lines, influenced by ambient conditions.; They show that their model leads to remarkably different static voltage stability assessment results compared to traditional models. [32] propose using FACTS tools such as SVC and STATCOM to improve voltage stability and FRT capability during the integration of wind power systems' [33][34]
Chu et al. [35] examine the issue of static voltage stability in systems with high IBG penetration. They propose an optimal system scheduling model aimed at minimizing overall system operation costs while ensuring voltage stability by dynamically optimizing the active and reactive power output from IBGs.
Abbass et al. [16] explore the application of an artificial intelligence network (ANN) to aid in training and predicting the nodal voltage level within the IEEE 4-bus system. Their findings suggest that the ensemble of models demonstrates superior performance in forecasting nodal voltage stability compared to other models for the electrical system.

2.1.2 System Control and Reconfiguration Approaches

This group of papers explores various control actions and system reconfiguration strategies aimed at preserving or enhancing voltage stability in the power system.
Lopez et al. [36] present a novel methodology for voltage stability control using angular indexes from stationary analysis. They propose control actions based on the cutset angle (CA) and center of angle (COA), with simulations confirming the importance of COA as an index to determine event locations and guide load shedding.

‘Palepu et al. [37] propose a method utilizing strategically placed phasor measuring units (PMUs) to monitor voltage stability margin online and regulate it with a static synchronous compensator (STATCOM). By identifying the minimum reactive and real power loadability for most line outages, STATCOM is installed at the critical bus. It supplies reactive power into the bus online as needed based on the discrepancy between the bus voltage and its reference value. PMU measurements determine bus voltages at regular intervals, with reactive power added to the bus online as required. The increase in voltage stability margin due to STATCOM injecting reactive power is continuously monitored. Through simulations conducted on the IEEE 14-bus system and the New England 39-bus system, the effectiveness of the proposed approach for online monitoring and management of voltage stability margin (VSM) is demonstrated’[38]

Alsadooni et al. [39] propose a combinational load shedding program that uses load frequency control; & ‘Voltage stability indicator to determine the minimum load shedding required to restore frequency and voltage within allowable ranges’[40].

Huang et al. [41] improve voltage stability by employing stochastic distribution network reconfiguration (SDNR).

They employ a deep learning method to predict voltage stability indices for optimized network topology, demonstrating computational efficiency and significant improvements in voltage stability.

‘Wu et al. [42] investigate the computation of the shortest path to the voltage stability boundary in systems with distributed energy resources (DERs)’[40]. ‘They propose a tri-sectional approximation model for large-scale systems, which achieves high accuracy and efficiency in approximating the shortest path to the stability boundary’[43].

2.1.3 Impact of Distributed Energy Resources on Voltage Stability

‘The incorporation of distributed generation (DG), encompassing renewable energy sources, into the power grid and its effects on voltage stability are the focus of several papers’[44][45].

‘Uzun et al. [46] examine the effect of solar photovoltaic(PV) generation systems on voltage stability. They determine the optimal location of PV system using continuous power flow(CPF) & bus voltage stability index demonstrating that appropriately sized and located PV systems can improve voltage stability’[47].

‘Prionistis et al. [48] proposes a framework to calculate the operational flexibility of an active distribution network, which is then used to address voltage stability margin maximization in a centralized optimal power flow problem by the transmission system operator’[49].

Aguirreangulo et al. [50] tackle the task of maximizing the voltage stability index in distribution networks by optimizing the placement and sizing of dispersed generators. Their research employs mixed-integer nonlinear programming to identify the optimal solution and validates the outcomes through recursive power flow equations.

An et al. [51] concentrate on addressing transient voltage instability resulting from AC faults in multi-infeed UHVDC systems. They suggest retrofitting shutdown thermal power units into synchronous condensers and introduce an optimal configuration method for this conversion. Liu et al. [52][53][54]

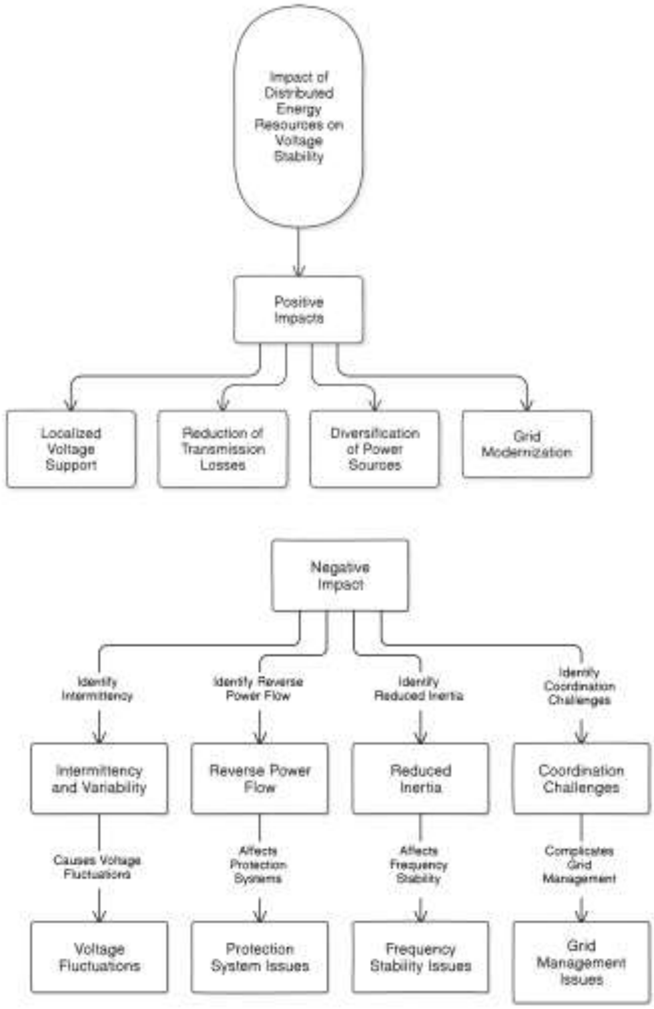


Fig.3. Impact on Voltage Stability

2.2 Research Gaps

While the reviewed literature offers a significant body of work on voltage stability analysis and control, several research gaps and discrepancies still exist that could be addressed in future studies. These areas include:

1. **Integration of High penetration of Renewables:** As renewable energy resources, such as wind and solar, are increasingly integrated into the power grid, their intermittent nature and impact on voltage stability require further investigation. Current studies may not fully address the challenges associated with the high penetration levels that are expected in the future, including the need for advanced prediction models that account for the stochastic nature of renewable generation.

2. Real-Time Voltage Stability Assessment: Many studies propose methodologies for real-time voltage stability assessment using advanced technologies like PMUs. However, there is a need for more research on real-time algorithms that are computationally efficient and capable of handling large volumes of data from PMUs, especially in complex and dynamic grid environments.

3. Impact of Electric Vehicles and Energy Storage: The increasing adoption of electric vehicles (EVs) and the use of large-scale energy storage systems present new challenges and opportunities for voltage stability. Research gaps exist in understanding how the charging and discharging patterns of these technologies affect the voltage profiles of the grid and how they can be effectively managed to enhance voltage stability.

4. Adaptation to Grid Topological Changes: While some studies explore the adaptability of voltage stability assessment methods to topological changes, there is a need for more robust methods that can quickly adapt to such changes, especially in the context of active distribution networks with high levels of DERs.

5. Cybersecurity Concerns: The dependency on advanced control systems and communication networks for voltage stability control introduces cybersecurity risks. Research on secure and resilient voltage stability control mechanisms that can withstand cyber-attacks is still limited.

6. Validation of Models and Indices: Although various new voltage stability indices and models are proposed, there is often a lack of extensive validation using real-world data and scenarios. Future research should focus on validating these models against practical operational conditions and ensuring that they are robust across different system configurations.

7. Economic Considerations: Many studies focus on the technical aspects of voltage stability, but research on the economic implications of implementing voltage stability control measures is less developed. Understanding the cost-benefit trade-offs of different strategies is crucial for their practical adoption.

8. Coordination of Control Devices: While FACTS devices, distributed generation, and load control strategies are individually studied, research on the coordinated control of these devices for optimal voltage stability enhancement is still emerging. There is a need for more sophisticated control algorithms that can manage the interdependencies between various control devices and system states.

9. Impact of Climate Change: The impact of climate change on the grid, such as increased temperatures and extreme weather events, can affect the voltage stability. Research on how to adapt voltage stability assessment and control methods to the changing climate conditions is still in its infancy.

10. Modeling and Assessment of Low-Voltage Networks: Most research focuses on transmission and high-voltage distribution systems, while low-voltage networks, which are

increasingly hosting distributed generation and active consumers, are less studied. Research on voltage stability in these networks, considering the unique challenges they present, is needed.
By bridging these disparities, forthcoming studies have the potential to advance the creation of power systems that are more resilient, efficient, and dependable, equipped to navigate the changing energy terrain.

2.3 Implications

Given the insights gleaned from the recent research in voltage stability analysis and control, the implications are both theoretical and practical, impacting the broader understanding of power systems as well as the strategies for maintaining grid reliability and efficiency.

Theoretical Implications

The recent findings contribute to the theoretical understanding of power systems by emphasizing the dynamic and stochastic nature of modern grids. Traditional theories of power system stability, which often assume static and deterministic conditions, are being challenged by the integration of higher levels of renewable energy sources that introduce variability and uncertainty into the system. The development of new voltage stability indices that account for stochastic inputs and the validation of models that incorporate the electro-thermal coupling effects of overhead lines under varying ambient conditions are critical theoretical advancements. These models and indices help refine our understanding of the complex interactions within power systems and the behavior under non-traditional operating conditions.
Furthermore, the exploration of distributed energy resources (DERs) and their impact on voltage stability pushes the theoretical boundaries of power system analysis into a more decentralized paradigm where control and stability are increasingly managed at the distribution level rather than centrally.

Practical Implications

Practically, the research outcomes have significant implications for power system operation and planning. For instance, the findings suggest that utilities and system operators must evolve their monitoring and control strategies to account for the impacts of renewable generation and DERs. Real-time voltage stability assessment tools that leverage PMU data can help operators make informed decisions to ensure grid stability. Additionally, optimal placement and sizing of DERs, as well as the strategic retrofitting of conventional power units into synchronous condensers, can enhance voltage stability margins and reduce the likelihood of voltage collapse.
These advancements have policy implications as well. Regulatory frameworks may need to be updated to incentivize the adoption of technologies that enhance voltage stability, such as energy storage systems and advanced inverter-based controls. Policies may also need to consider the economic trade-offs associated with implementing voltage stability control measures, balancing the cost of investments against the benefits of improved grid reliability.
For future research directions, the need to focus on cybersecurity in voltage stability control systems is evident, as is the importance of developing coordinated control strategies for various grid-supporting devices. Additionally, understanding the economic implications of voltage stability measures will be crucial for their practical implementation.
In summary, the theoretical advancements in voltage stability analysis contribute to deeper

understanding of the modern power grid's behaviour, while the practical implications suggest a roadmap for industry and policymakers to improve grid reliability and efficiency in an evolving energy landscape. These findings underscore the importance of continued research & innovation in this field to the challenges of the 21st-century energy landscape.

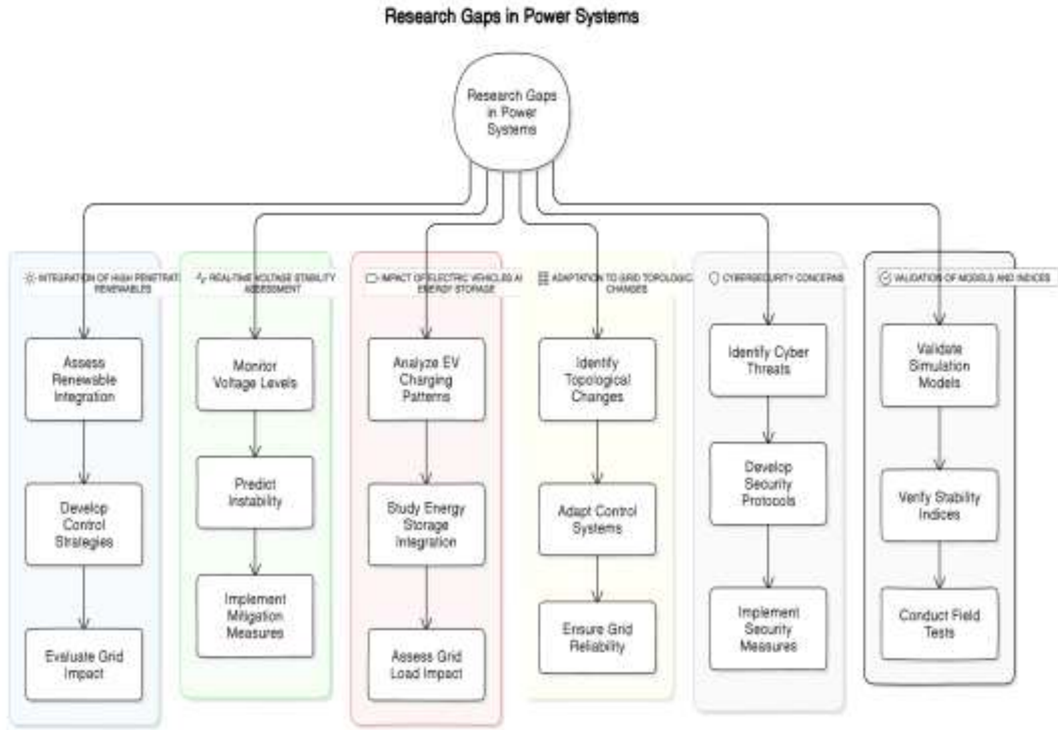


Fig.4a. Research Gap in Power System

3. OPTIMIZATION TECHNIQUES

3.1 Findings

Given the provided information, there is only one paper to summarize. Below is the summary of the key findings from the perspective of Optimization Techniques:

3.1.1 Optimization of Power Transmission Systems using Rapid Voltage Stability Index & Grey Wolf Algorithm

The paper by Muppidi et al. [55] addresses the optimization of power transmission systems with a specific focus on enhancing line loadability while minimizing fuel costs. The authors apply a novel approach that integrates Rapid Voltage Stability Index & Grey Wolf Algorithm (GWA) to solve optimal power flow(OPF) problem

The key findings of the paper can be summarized as follows:

In conclusion, the paper [55] contributes to the field of power system optimization by providing an effective technique that can simultaneously enhance system stability and reduce operational costs. The use of advanced algorithms such as GWA alongside stability indices like RVSI represents a promising direction for future research and application in power system optimization.

3.2 Research Gaps

3.2.1 Research Gaps and Future Directions

While the study by Muppidi et al. [55] makes significant strides in the optimization of power transmission systems, there remain several research gaps and opportunities for further exploration:

1. **Scalability and Practical Implementation**: The research was conducted on a standerd IEEE 30 bus test system. However, real-world power systems are often more complex and larger in scale. It is essential to investigate the scalability the proposed method and its efficacy on systems with a higher number of buses and more intricate network topologies.

2. Integration with Renewable Energy Sources: With the growing incorporation of renewable energy sources into the grid, the variability and uncertainty associated with these sources need to be considered in optimization strategies. Future research could focus on adapting the RVSI and GWA technique to accommodate the dynamics of renewable energy integration.

3. Comparison with Other Optimization Techniques: The study primarily explores the use of the Grey Wolf Algorithm. An analysis comparing GWA with other evolutionary algorithms or optimization techniques could provide insights into the relative effectiveness and robustness of different methods under a variety of system conditions.

4. Regulatory and Market Constraints: The paper focuses on technical aspects of line loadability and fuel cost minimization. However, power systems operate within regulatory and market frameworks that impose additional constraints. Further research could incorporate these aspects to assess the practicality of implementing the proposed optimization solutions in real-world market conditions.

5. Resilience to Cyber-Physical Threats: The increasing digitalization of power systems exposes them to cyber-physical threats. Future studies could explore the resilience of optimized power systems using RVSI and GWA against such threats and develop strategies to mitigate potential risks.

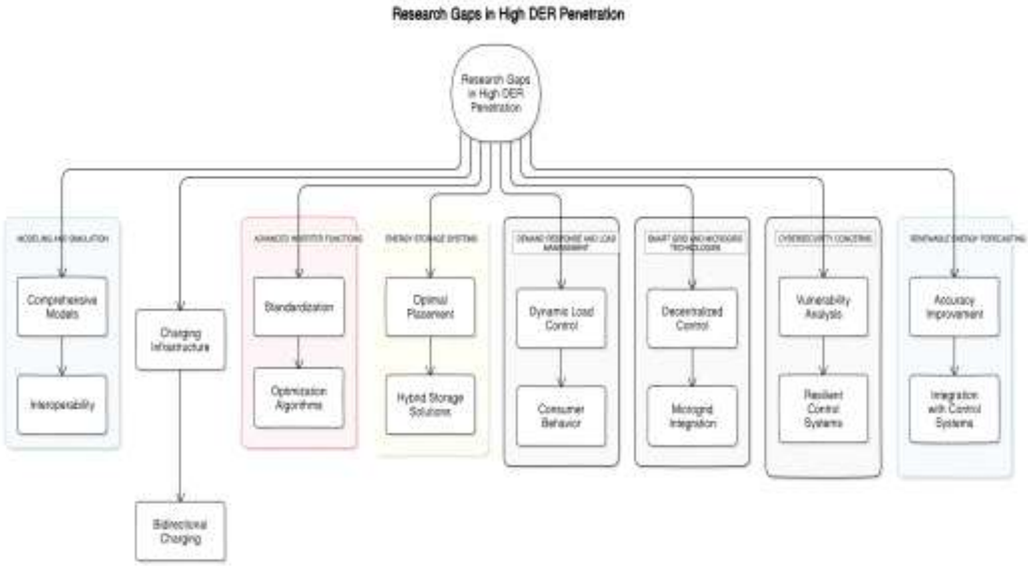
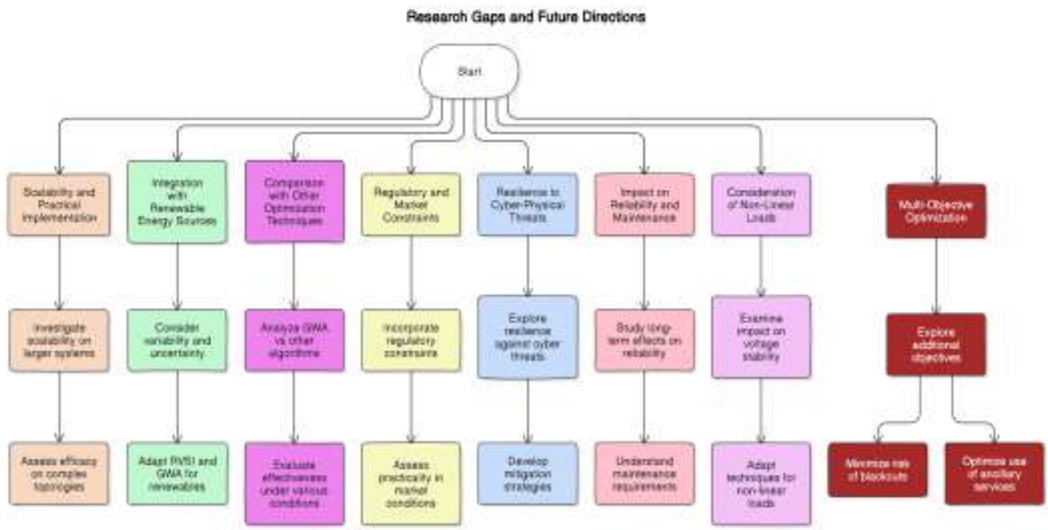


Fig.4a. Research Gap in Power System

6. Impact on Reliability and Maintenance: The long-term effects of optimized line loadability on the reliability and maintenance schedules of power transmission equipment are not addressed in the study. Research is needed to understand how these optimization techniques might influence maintenance requirements and system reliability over time.



7. Consideration of Non-Linear Loads: The behavior of non-linear loads and their impact on voltage stability
and power quality could be further examined. Adapting optimization techniques to effectively manage systems with a significant proportion of non-linear loads would be a valuable area of research.

8. Multi-Objective Optimization: While the study considers various objectives such as cost, emissions, and voltage deviation, there is a potential to explore additional objectives that may be relevant to stakeholders, such as minimizing the risk of blackouts or optimizing the use of ancillary services.
In conclusion, while the paper by Muppidi et al. [55] has laid a foundation for optimizing transmission systems using RVSI and GWA, the aforementioned gaps highlight the need for continued research to address the evolving challenges of modern power systems and to ensure that optimization techniques remain effective in an ever-changing energy landscape.

3.3 Implications

3.3.1 Implications of Optimization Techniques in Power Transmission

The practical implications of the findings from Muppidi et al.'s study [55] on the optimization of power transmission systems are significant for both policy and industry practice. By demonstrating the effectiveness of the RVSI and GWA for enhancing line loadability and reducing operational costs, this research could inform the development of more efficient and cost-effective power transmission strategies. Utilities and system operators might consider incorporating these techniques into their operational planning to alleviate congestion, manage fuel costs, and ensure voltage stability, which is crucial for maintaining a reliable power supply.
From a policy standpoint, the study's outcomes could encourage regulators to adopt standards and incentives that promote the use of advanced optimization algorithms in power system operations. Such policies could lead to wider adoption of efficient practices that not only support the stability of the grid but also contribute to environmental objectives by optimizing the generation mix and reducing carbon emissions.
For future research directions, this study underscores the importance of algorithmic innovation in addressing complex power system challenges. Researchers may explore the integration of the GWA with other optimization methods or the development of hybrid algorithms that can better handle the complexities of larger-scale and more diverse power systems, including those with high penetration of intermittent renewable energy sources.
Theoretically, the validation of RVSI & GWA in optimizing power systems supports the broader understanding of how heuristic and metaheuristic algorithms can be tailored to specific industry requirements. This contributes to the ongoing discourse on the applicability of such algorithms in real-world scenarios, potentially challenging existing theories on optimization that are based on more traditional mathematical programming techniques. The study also suggests that the theoretical framework of power system stability and optimization must account for the dynamic nature of modern grids, which are increasingly influenced by distributed generation sources, demand response technologies, and digitalization.

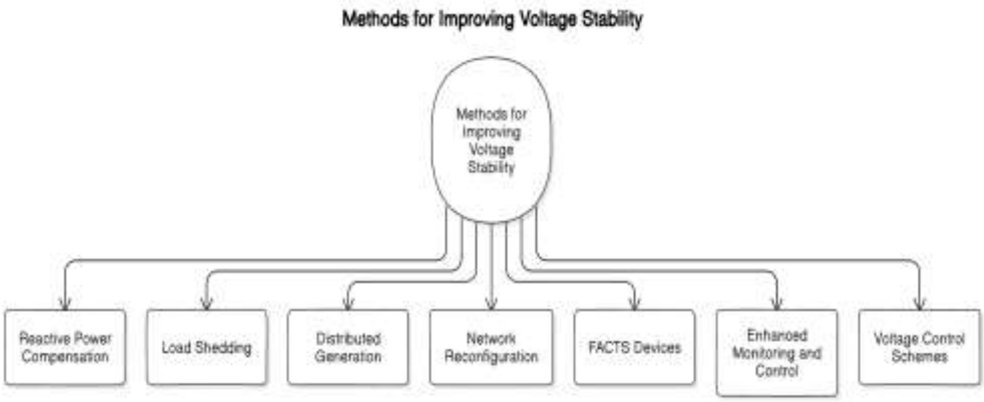


Fig.6. Voltage Stability Improving Methods

In conclusion, the research by Muppidi et al. [35] has both theoretical and practical significance. It enriches the theoretical landscape of power system optimization and

offers practical insights that could influence future technology development, industry practices, and policymaking to create more resilient and cost-effective power systems.

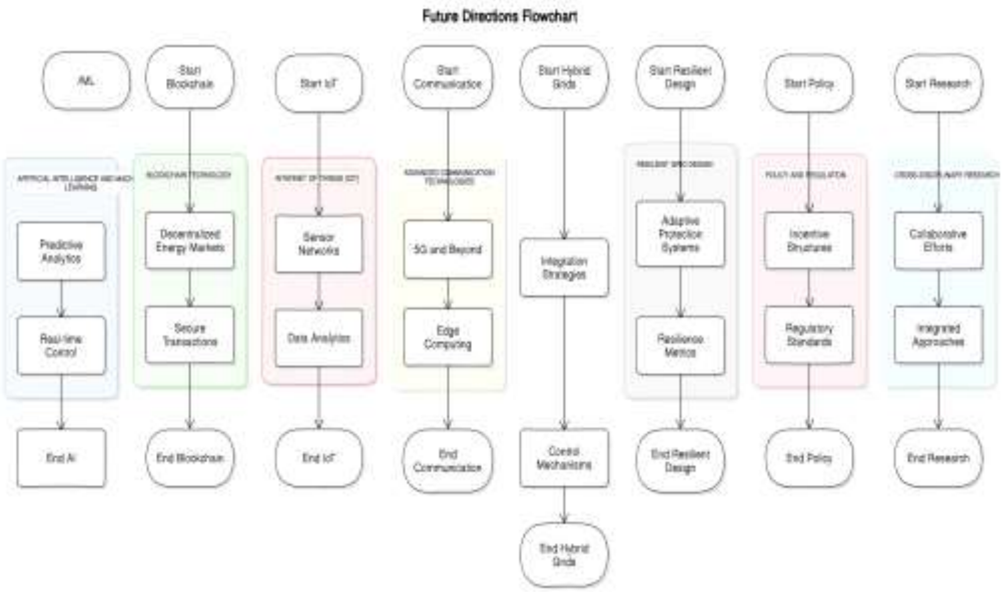


Fig.7. Future direction of Voltage Stability

4. CONCLUSION

In conclusion, the reviewed literature provides valuable insights into the ongoing research related to voltage stability analysis and control, which remains an important area of study given the changing characteristics and operational challenges of modern power grids. Several gaps and opportunities for future work have been identified, such as improved methods for renewable energy integration, real-time stability assessment, impacts of new technologies like EVs and storage, and validations through field testing and real system data. Addressing these gaps through continued research efforts will help develop more robust and adaptive solutions that support reliable grid operations in the face of ongoing energy transitions.

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