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Navigating Renewable Energy Challenges: Insights into Stability, Control, and Optimization

[1]Mukesh Paswan and [2]Pramod Kumar Rathore,
[1]MTech Scholar, [2]Assistant Professor,
[1,2]RKDF College of Engineering Bhopal, Madhya Pradesh, India

Abstract – The increasing penetration of renewable energy sources (RES) has significantly transformed power systems, introducing challenges related to stability, control, and efficiency. This review consolidates recent advancements in addressing power system stability issues, focusing on power angle stability, frequency stability, voltage stability, and system inertia constraints. Innovative approaches such as grid-forming inverters, reactive power coordination, and advanced modeling techniques are explored. Furthermore, methodologies for integrating intermittent RES while maintaining operational reliability are analyzed. The findings emphasize the importance of coordinated control strategies, novel algorithms, and stability assessment frameworks for ensuring seamless RES integration in modern power grids.

Keywords: *Renewable Energy Penetration, Frequency Stability, Voltage Stability, Grid-Forming Inverters, Reactive Power Coordination, Stability Assessment.*

I. INTRODUCTION

The rapid shift toward renewable energy sources (RES) has revolutionized power generation globally, driven by environmental concerns and policy mandates. Solar, wind, and other intermittent sources now dominate power generation, replacing conventional synchronous generators. While this transition supports sustainability goals, it also introduces complex challenges to power system stability.

Key concerns include frequency and voltage stability, system inertia reduction, and the limitations of traditional control mechanisms. The inherently unpredictable and intermittent nature of RES necessitates innovative solutions to mitigate stability risks and maintain grid reliability. Researchers and engineers are actively exploring methodologies to address these challenges, ranging from advanced control systems to enhanced modeling techniques.

This review aims to provide a comprehensive analysis of recent advancements in power system stability under high RES penetration. The reviewed studies highlight innovative approaches to ensure frequency and voltage stability, assess system inertia, and integrate modern power electronic technologies. The findings offer valuable insights for developing resilient power systems in an era of renewable energy dominance.

II. LITERATURE REVIEW

The transition to renewable energy sources (RES) has introduced complex challenges to power systems, prompting extensive research into stability, control, and optimization techniques. Recent studies provide valuable insights into addressing these challenges.

Houyi Zhang (2023) With the high renewable energy(RE) penetration, the power system is facing more and more stability issues. Among them, the power angle stability(PAS) and frequency stability(FS) have close association with the power generation status. A generation optimization planning method integrating PAS and FS is proposed in this paper, which incorporates the power angle stable cut constraint obtained through PSAT based on EEAC, and frequency stable cut constraint obtained through Simulink based on equivalent frequency response model, achieving the stability requirement while ensuring economic efficiency. The approach collaborates the construction of thermal power units, wind power, solar power and energy storage using the column and constraint generation algorithm. The advantages of the proposed approach are validated through a provincial power system in China.

Wenbin Cai (2023) The proportion of intermittent renewable energy has rapidly increased, and gradually become the main form of power generation. Under massive planning and construction of renewable energies, the rotating inertia of regional power system shows a gradually decreasing trend which weakens the power system's frequency stability, so it is necessary to take the system inertia as a constraint index in future high penetration renewable development planning. This paper introduces a method to estimate the inertia and the minimum inertia limit for traditional power system and for future high renewable penetration power system including virtual inertia of renewable generation. An actual provincial power system is used in this paper as the case study to analyze the trend of system inertia and minimum inertia constraint under massive renewable development.

M. A. Hossain (2023) The emergence of smart grids has introduced new challenges to traditional power system control due to the increasing number of risk factors. This paper presents a parameter tuning strategy using an optimisation algorithm to optimise the weights of the objective function. This enhances the adaptive control capabilities of online supplementary control to address the complexities of power system control in smart grids and offers a promising solution for improving overall system performance. The proposed online control, based on approximate dynamic programming, operates in conjunction with an existing power system controller. The results demonstrate the effectiveness of the proposed approach in maintaining frequency within acceptable limits. Comparative studies are performed against conventional frequency control strategies to highlight the advantages of the proposed method. The findings of this study contribute to the development of efficient and adaptive frequency control strategies for power systems with high renewable energy penetration.

A. Zapata (2023) In order to reach global objectives of minimizing environmental impacts attributed to power systems, further implementation of renewable energy sources is necessary. However, planning high penetration of renewables presents new control challenges for current power systems since most new technologies are power electronics based. This paper presents a methodology to evaluate possible control issues and solutions to guarantee system wide stability and identify weak points under high penetration of IBRs. The methodology uses both transient stability and system strength assessment of existing and planned IBR installations. Several system strength metrics are computed considering N-0 and N-l contingencies. For the transient stability analysis, key parameters of the IBR dynamic model are adjusted to identify possible stability issues by the simulation of selected contingencies. The methodology identifies weak points in the power grid and control settings in the power plant and inverter controllers that negatively affect system stability. This methodology was evaluated with information from a utility company. The results suggest future points that require additional studies and a list of recommendations to include in stability guidelines for the secure interconnection of new IBRs in the Bulk Power System.

W.M.R.N. Wijethunga (2023) Integrating intermittent non-conventional renewable energy sources such as wind and solar into power systems presents unique challenges for its operation. To address this, effective frequency control mechanisms are crucial. This study presents a comprehensive analysis investigating the performance of hydro and steam, in a non-conventional renewable integrated power system. The analysis aimed to enhance power system stability through the collective operation of wind and solar power plants of varying capacities, while maintaining a stable frequency. In addition, the study investigated the maximum penetration level of these resources under different contingencies. Preliminary results indicate that the hydro turbine exhibits a longer settling time and higher steady-state error compared to its steam turbine counterpart. Using a 12 bus test system simulated in PSCAD software, this research provides valuable insights into turbine performance and the feasibility of integrating renewable resources, aiding in the improvement of power system stability.

Liang Wang (2022) The large-scale integration of renewable energy brings a great challenge to the voltage stability and reactive power balance of power grids. Unpredictable, intermittent, and irregular renewable energy sources can amplify the voltage fluctuations greatly. Thus the problem of power surplus emerges more frequently, leading to a more difficult control task. For renewable energy power plants in certain locations, it is beneficial to make use of the seasonal information and the pattern of power generation during the day or night. Meanwhile, the utilization of the traditional Automatic Voltage Control (AVC) and the coordination of the reactive power resources among different power plants can help to maintain the reactive power balance and the voltage stability in the regional power grids. Therefore, this work establishes a reactive power and voltage distribution model for the renewable energy power plants. Furthermore, based on this model, it proposes a coordinated control strategy for reactive power and voltage, by taking into account the coordination of various time scales as well as multiple reactive power resources. It has been shown to achieve a more stable control for reactive power and voltage in regional power grids. The results are validated via comprehensive simulation studies.

Chenyang Li (2022) With the penetration rate of renewable energy has been rapidly increasing in power system, synchronous generators (SGs) are gradually replaced by power electronics. However, wind turbines and photovoltaics nearly have none moment of inertia, they exhibit grid-following characteristics and can’t provide effective support. As a result, grid-forming inverters (GFMs) are proposed for improving the grid stability. In this article, the transient response of GFMs with droop and virtual synchronous generator (VSG) methods are studied, and motor-generator pair (MGP) with improved power control is proposed as a novel grid-forming method. Frequency stability of grid-forming inverters, SGs and MGPs considering control delay and current limitations are studied through IEEE standard 3-generator 9-bus system to demonstrate the differences between grid-forming methods and required characteristics for frequency stability, this article provides a broader view for grid-forming.

Manohar Singh (2022) Penetration of high renewables impacts the steady state and dynamic operational behavior of a power network. The voltage profiling in a power system is depended on the reactive support provided by generating resources. The renewables generating resources has limited support for voltage control as compare to conventional power generating resources. The voltage stability is an inherent problem associated with high penetration of renewables in power systems. This article provides a steady state voltage stability analysis for an IEEE39 bus systems under high penetration of solar and wind power. Different operational scenarios with wind, solar and mix of both have been studied to investigate the voltage stability issues in this IEEE-39.The simulation work is performed in PSSE software using Newton-Raphson’s method to compute the power flow a for mix of generation from renewable resources. It is observed that the incremental percentage of electricity generated by renewable energy sources affects the voltage stability of the system and finally this may lead to voltage instability beyond a limited of renewables penetration.

Lizong Zhang (2022) The power electronic based photovoltaic power generation, wind turbine and other renewable power generation systems have the potential of millisecond level power control. Based on the analysis on the demands of fast power control in grids with high renewable generation penetration, this paper proposes the structure of fast renewable energy power control system. The information transmission delay, MCU processing delay and the MPPT tracking delay are analyzed. A novel algorithm is implemented to enable the renewable power generations to quickly respond to the control commands from the power grid and realize rapid bi-directional power adjustments. The proposed methods could participate in the primary frequency and voltage regulation in the power grid.

Xiangyang Wu (2022) Medium-voltage direct current (MVDC) systems are increasingly used for renewable energy sources (RESs) integration and transmission with rapid improvements in power electronic technologies. However, some instability issues may arise due to the dynamic interactions among RESs, converters, and ac grid. This paper proposes a framework of small-signal modeling and stability assessment methods for MMC-MVDC systems with high penetration photovoltaics (PVs). First, a systematic hybrid impedance modeling method for MMC-MVDC system is developed. Then, based on the established model, a hybrid impedance criterion is proposed to evaluate the stability of MMC-MVDC system. And the stability properties of MMC-MVDC are investigated via generalized Nyquist plots. Finally, the time-domain simulation results verify the effectiveness of the proposed small-signal stability assessment method based on the hybrid impedance stability criterion.

CONCLUSION

The integration of renewable energy sources into modern power grids presents significant technical challenges, particularly in stability and control. This review underscores the critical advancements in addressing these challenges, including optimized generation planning, innovative control strategies, and advanced modeling techniques. Solutions such as grid-forming inverters, reactive power coordination, and stability assessment frameworks have proven effective in mitigating the risks associated with high RES penetration.

Future research should focus on enhancing the scalability and interoperability of these solutions across diverse grid configurations. Collaborative efforts among researchers, policymakers, and industry stakeholders are essential to ensure the seamless integration of renewables while maintaining grid reliability and stability. By adopting these innovative strategies, power systems can achieve sustainability goals without compromising operational performance.

References

[1] H. Zhang et al., “Incorporating power angle stability and frequency stability in generation optimization planning with high renewable energy penetration,” in 2023 IEEE International Conference on Energy Internet (ICEI), 2023, pp. 321–325.

[2] W. Cai et al., “High renewable penetration development planning under system inertia constraints,” in 2023 6th International Conference on Energy, Electrical and Power Engineering (CEEPE), 2023, pp. 819–823.

[3] M. A. Hossain, E. M. Gray, J. Lu, M. S. Alam, W. Hassan, and M. Negnevitsky, “Optimised online adaptive frequency control of power system with renewable energy penetration,” in 2023 IEEE International Conference on Energy Technologies for Future Grids (ETFG), 2023, pp. 1–4.

[4] A. Zapata, D. Santos, D. Wu, and D. Rodríguez, “High penetration of inverter based resources assessment on stability and system strength,” in 2023 IEEE Power & Energy Society General Meeting (PESGM), 2023, pp. 1–5.

[5] W. M. R. N. Wijethunga, P. A. H. K. Wijesena, T. D. Samarawickrama, and D. P. Wadduwage, “Frequency stability analysis of non-conventional renewable integrated power systems,” in 2023 Moratuwa Engineering Research Conference (MERCon), 2023, pp. 90–94.

[6] L. Wang et al., “Research on coordinated reactive power and voltage control strategy for regional power grids with high penetration of renewable energy,” in 2022 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia), 2022, pp. 1160–1165.

[7] C. Li, Y. Huang, H. Deng, and X. Zhang, “Comparison on frequency stability of high inverter penetration power system with different grid-forming controls,” in 2022 International Conference on Power Energy Systems and Applications (ICoPESA), 2022, pp. 374–380.

[8] M. Singh, M. H, and V. H, “Investigation on power system stability with integration of renewable resources,” in 2022 IEEE 10th Power India International Conference (PIICON), 2022, pp. 1–6.

[9] L. Zhang, L. Ding, J. Yao, W. Ru, X. Shen, and G. Xu, “Research on the cascaded fast power control system for renewable generations,” in 2022 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia), 2022, pp. 806–810.

[10] X. Wu, W. Huang, Y. Li, L. He, Q. Zhou, and Z. Shuai, “Small-signal stability assessment method for MMC-MVDC system with high penetration PV based on hybrid impedance stability criterion,” in 2022 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia), 2022, pp. 1190–1195.