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Review

Guest Editorial: Control interactions in power electronic converter dominated power systems

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ABSTRACT

Guest Editorial.

1. Introduction

The modern power systems have undergone significant transformations at the generation, transmission, distribution, and utilization levels due to the remarkable advancements in power electronic converter technology. Power electronic converters are now prevalent in various applications, including wind turbine converters, photovoltaic inverters, flexible AC transmission systems (FACTS) and high-voltage DC (HVDC) converters, distributed generators, microgrids, and electric vehicles. The widespread adoption of power electronic converters has revolutionized the power system by providing fast and flexible controllability. However, their unique characteristics, such as fast response, multi-time scale dynamics, reconfigurable control, and varying sizes and capacities, have introduced new stability challenges, fundamentally altering the dynamics of modern power systems [1].

On the generation side, the introduction of converter-interfaced generators has transformed the traditional approach to power generation using synchronous generators. These converter-interfaced generators exhibit features such as input resource intermittency and smaller unit sizes with low or synthetic inertia. Consequently, the generation side faces distinct stability challenges that differ from classical stability problems.

In terms of transmission, the proportion of FACTS and HVDC converters has increased and is expected to continue growing. FACTS and HVDC converters have enhanced power transmission by providing greater flexibility in controlling power network parameters and transmitting power over longer distances. However, the expanded utilization of FACTS and HVDC has also introduced new control and stability challenges.

At the distribution level, small-scale converter-interfaced generators, electric vehicles, and inverter-based battery energy storage systems have significantly complicated distribution and utilization systems. These developments have profoundly impacted the dynamics of modern power systems.

These converter-based devices and their controls in modern power systems tend to interact with each other and other power system components. The converter control-participated interactions give rise to oscillations encompassing a wide frequency range from a fraction of hertz to several kilohertz, commonly known as wideband oscillation [2].

Over the past decade, numerous instances of wideband oscillation

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have been reported worldwide. Examples include incidents in ERCOT's wind bases in Texas, USA; First Solar's solar farms in California, USA; Southeast and West-Murray zones in Australia; Hornsea offshore wind farm in the UK; and Guyuan/Hami wind bases and Nan'ao/Luxi HVDC systems in China, among others. The active involvement of converter controls significantly influences these interactions. Moreover, the interaction mechanisms become more intricate due to system-wide factors such as the intermittent nature of input resources, power generation from converter-interfaced generators, converter control parameters, network topology, and grid strength. Consequently, studying the complex phenomena of control interaction and devising appropriate countermeasures pose substantial challenges.

The presence of wideband oscillation represents a significant obstacle in achieving stable operation in modern power systems characterized by a higher share of renewables and power electronics. This Special Issue "*Control Interactions in Power Electronic Converter Dominated Power Systems*" seeks to investigate mechanisms, detection, modeling, analysis, control, and mitigation of the emerging wideband control interactions involving power electronic converter-based devices.

In this remarkable Special Issue, submissions were received from authors worldwide, and the Guest Editorial Board meticulously conducted an extensive review process, resulting in the approval of 18 exceptional papers for publication. These papers encompassed innovative ideas concerning modeling and analysis and control methods suitable for power systems integrating power electronics, analysis of emerging stability issues, and advanced converter control technologies wideband oscillations. The Guest Editorial Board extends heartfelt gratitude to all the authors who contributed their latest research to this Special Issue. Their valuable work has positively contributed to the power system academics and engineers.

Furthermore, the Guest Editorial Board sincerely appreciates the anonymous reviewers for their invaluable suggestions and constructive comments, which played an instrumental role in ensuring the quality and rigor of the published papers.

The Guest Editorial Board would also like to acknowledge the journal Editorial Board for providing the opportunity to organize this Special Issue. Their support and encouragement have been invaluable in making this endeavor a success. Additionally, the journal production team deserves thanks for their efficient technical support throughout the process, from the call for papers to the operation of EVISE and the production of the accepted papers. The collaboration with the journal and production team has been immensely gratifying. It has been a delightful experience working with all the individuals involved in organizing and producing this Special Issue, and their contributions have been truly appreciated.

2. Review of topics addressed

This section summarizes the topics and the papers included in this Special Issue.

2.1. Oscillation mechanisms and risk assessment

The authors of [3] investigate the cause of ultra-low frequency oscillation (ULFO) in a system consisting of hydraulic generators and a weak ac grid. A small-signal model of a two-machine system is developed to analyze the oscillation characteristics by examining different thermal-hydro power proportions. The findings reveal that while a higher proportion of hydropower results in a lower oscillation frequency, it is not the primary cause of ULFO. The analysis shows that weak grid conditions, rather than the hydropower proportion, are the essential cause of ULFO. The connection strength of the system determines its susceptibility to ULFO, with the governor playing a crucial role in weak grid conditions. Simulation results confirmed the theoretical analysis, demonstrating that a system with all thermal power can still experience ULFO in weak connections. In contrast, a strong connection prevents ULFO even with all hydraulic generators. Additionally, in weak grid conditions, the hydropower proportion worsens the ULFO problem, as evidenced by decreased oscillation frequency and damping ratio.

In another work [4], the authors examined control interactions between synchronous machines and inverter-based resources (IBRs) in power systems dominated by IBRs. The study identified potential oscillation risks through modal impedance analysis and electromagnetic transient simulation and investigated various factors' impacts. The results showed that high penetration of grid-following IBRs could lead to oscillation instability, which can be mitigated by adjusting control parameters. Furthermore, replacing some grid-following converters with grid-forming converters can eliminate oscillation modes. Overall, the study highlights the importance of understanding control interactions in IBR-dominated systems for ensuring stability.

The authors in [5] explored the mechanism of the dynamic interaction between power electronics-based substations of flexible traction power supply systems (FTPSS). The authors used the frequency domain model of the FTPSS with power-sharing control. The eigenvalue analysis is further used to study the effect of control parameters and communication time delay on the stability of the interconnected system.

2.2. Stable region estimation to avoid control interactions

The authors of [6] focused on the detection and continuation of the Hopf bifurcation associated with subsynchronous oscillations (SSO) in DFIG-based wind farms. To address the limitations of standard numerical continuation packages for studying SSO in large-scale power systems, the authors propose a simplified test function that considers only the subsynchronous and supersynchronous modes. These modes are computed using an adapted version of the selective modal analysis (SMA) iterative method, which avoids the computation of all system eigenvalues. The iterative procedure for Hopf bifurcation detection and the standard prediction-correction routines for its continuation are customized to accommodate the proposed test function and SMA-based eigenvalue computation. The methodology is demonstrated on a relatively large-scale system comprising 11 wind farms with 22 aggregated models and 690 state variables.

In another research [7], the authors proposed an impedance network-based oscillatory stability analyzer (INOSA), which is a MATLAB-based application package. INOSA only uses known system data and at least ten impedance measurements as input to the software in excel format. With correct input data, it maps out the operating points such that the boundary of operating points leading to stable and unstable system is identified. The INOSA is validated on a simplified model of an actual system facing the SSO.

The authors of [8] developed a simplified large-signal model of a DC microgrid system with virtual DC machine control using the Takagi-Sugeno (TS) fuzzy modeling method. This model addresses the challenge of accurately determining the system's stability region, considering the nonlinearity introduced by power electronics-based loads with constant power characteristics. The authors proposed an approach to estimate the asymptotic stability region, which provides insights into the maximum allowable changes in the DC bus voltage and load power. The accuracy of the proposed model and the effectiveness of the methods are verified through simulations and experiments.

2.3. Analysis and investigation approaches of converter dominated power systems

The Special Issue covered the analysis and investigation of the wideband oscillations resulting from control interactions in converter-dominated power systems. Below, we present a summary of the papers presenting different approaches.

The authors of [9] presented an alternative impedance-based analysis method to identify mode frequencies and assess the participation of impedance components in low-frequency interactions in power systems. This method is compared to the conventional approach of approximating mode frequencies using the gain and phase crossover of the impedance ratio. The study focuses on the low-frequency range, specifically below 100 Hz, where voltage source converter outer loops and synchronous generator circuits and controls play a significant role. The authors explore the simplification of synchronous generators as Thévenin equivalents based on impedance frequency response. An essential power system model comprising a voltage source converter, a synchronous generator, and a load is presented to demonstrate the advantages of the alternative impedance-based analysis.

The authors of [10] proposed a modified method for calculating modal frequency sensitivity (MFS) in modal sensitivity analysis (MSA) in power electronic systems. The conventional MSA suffers from inaccuracies due to frequency resolution limitations. The proposed method solves the critical variable expression using a non-homogeneous formula, eliminating the influence of frequency resolution and significantly improving accuracy. Additionally, the authors introduce the concept of modal resonance sensitivity (MRS) to quantify the sensitivity of resonance peak impedance to parameters. MRS is adaptable to changing resonance frequencies and complements the analysis of modal impedance sensitivity (MIS). Both methods provide precise guidance for designing resonance mitigation and suppression schemes in power electronic systems. The proposed approach is validated through time-domain simulations involving multiple converters.

2.4. Methods to mitigate the control interactions

The control interaction issues in grid-connected inverters (GCI) can be mitigated at the unit level by modifying the converter control design, for instance, by improving the inner current control structure or upgrading the phase-locked loop (PLL). The PLL bandwidth and design are crucial in the control interaction between GCI and weak ac grid.

The authors of [11] addressed the sub-synchronous resonance (SSR) issues observed between grid-connected wind farms and weak grids. The coupling mechanism between the GCI and weak grid is analyzed based on the power angle relationship, revealing a small signal coupling between d-axis current and power angle caused by the grid impedance. This coupling destabilizes the system through PLL feedforward paths, explaining the limitations of weak grid and PLL bandwidth. To dampen SSR, the authors proposed a d-axis current error compensation method, which introduces an additional parallel branch to compensate for the PLL feedforward effect and increase the dq-axis impedance amplitude of GCI. This reduces the coupling between GCI and weak grid. Experimental results validated the theoretical analysis and demonstrated the effectiveness of the proposed compensation method.

The authors of [12] analyzed the mechanism and characteristics of SSR in the GCI system under a weak grid using an impedance model, revealing that the asynchrony of system frames and control frames is the main factor affecting system stability. The authors proposed an alternative phase compensation method for the PLL to suppress SSR. The method introduces a compensation frame to reduce the angle difference with the system frame, enhancing grid strength and providing damping to the system. The authors also introduced virtual resistance and reactance through reactive power to further improve damping but at the cost of limiting power transfer capability. Finally, the authors demonstrated the effectiveness of the proposed method through experimental results and theoretical analysis.

The authors of [13] investigated the sub/super-synchronous oscillations caused by control interaction between grid-connected inverters and weak grid conditions through eigenvalue analysis. Based on the participation factor analysis, the authors identified the PLL as the dominant factor contributing to SSO. A new method was proposed to determine the optimal range of the PLL phase margin to suppress sub/super-synchronous oscillations under weak grid conditions. The proposed suppression strategy was validated through simulations and experimental studies, demonstrating its effectiveness in weak grid integration of inverters.

In [14], the authors addressed the control interaction between type-3 wind farms and series compensated transmission lines. The authors proposed an event-triggered sliding mode control (ETSMC)-based approach to effectively dampen the SSO. The ETSMC is applied to the rotor side converter of the type-3 wind turbine generator, and a phase compensator unit is added to enhance its effectiveness in mitigating specific unstable modes. The proposed control approach is validated on a modified IEEE first benchmark model, demonstrating fast system recovery.

The authors of [15] addressed the damping and coupling characteristics of grid-forming converters in a multi-vendor interoperability-based network. It proposed an analytic method based on participation factor analysis to analyze the oscillatory modes and coupling characteristics in the grid-forming converter-based network, considering different control techniques. The authors further proposed a hybrid damping method using an oscillation damper and a decoupling controller. The authors also provide design guidelines to identify the optimum parameters of the hybrid damping approach. Finally, controller-hardware-in-the-loop (CHiL) simulation results validate the theoretical analysis and demonstrate efficient damping against large disturbances.

The authors in [16] proposed a broadband active damping method for addressing high-frequency resonance (HFR) caused by negative damping in modular multilevel converter (MMC) impedance. The method utilizes phase compensation to eliminate negative damping over a wide frequency range (500–2000 Hz). It performs better in suppressing HFR under varying grid conditions compared to existing solutions using digital filters. The effectiveness of the method is validated through time-domain simulations.

3. Relevance to the IJEPES

Modern power systems suffer a wide range of stability challenges mainly driven by high penetration of power electronic converter-based devices and renewable power generators. This section summarizes the papers that appeared in this Special Issue relevant to IJEPES.

The authors of [17] investigated the impact of dual-sequence phase locked loops (PLLs) on the dynamic stability of converter-based renewable energy generation systems during asymmetrical low voltage ride through (LVRT) in weak grids. In this study, the authors revealed that dual-sequence PLLs introduce more modals with weak damping and change the unstable modal compared to single-sequence PLLs, due to complex dynamic interactions. Consequently, stability conclusions and control strategies for single-sequence PLL systems are not applicable to dual-sequence PLL systems. Furthermore, the paper identified the cause of small-signal instability in VSC during asymmetrical LVRT with dual-sequence PLLs. It analyzed the influence of control parameters in current control loops on dynamic performance. Furthermore, the authors also proposed an improved control scheme to enhance the dynamic stability of dual-sequence PLL systems during asymmetrical LVRT. Finally, the authors validated the proposed method through simulations and experiments.

The authors of [18] addressed the trade-off between DC link voltage dynamics and AC-side current quality in grid-interfacing power converters. The trade-off limits the achievable DC link voltage loop bandwidth while maintaining a desired grid-side current total harmonic distortion (THD). Previous studies introduced a notch filter to mitigate this trade-off but required a complete controller redesign. In this paper, the authors proposed a plug-in disturbance observer to replace the notch filter. This approach allows for an increased DC link voltage loop bandwidth without modifying the existing DC link voltage controller. A special frequency-selective filter is used to achieve this improvement. Simulation and experimental results validated the effectiveness of the proposed methodology.

4. Closing remarks

This Special Issue focused on the mechanism of new types of interactions, modeling, analysis, and control approaches to minimize the risk of wideband oscillation caused by control interactions in converter-dominated power systems. The published research showcased advancements in enhancing the performance of power electronic converter-based devices such as type-3 wind turbines, type-4 wind turbines, and HVDC inverters. Several papers also investigated the control interactions caused by different converter control structures, such as grid following and grid forming controls, and how these new types of converters can mitigate the control interactions.

The Guest Editorial Board hopes that the readers of this Special Issue find it a valuable source of information for future research and advancement of the field.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] Shair J, Li H, Hu J, Xie X. Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics. Renew Sustain Energy Rev 2021;145:111111. https://doi.org/10.1016/j.rser.2021.111111.

[2] Cheng Y, Fan L, Rose J, Huang S-H, Schmall J, Wang X, et al. Real-World Subsynchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources. IEEE Trans Power Syst 2023;38(1):316–30.

[3] Wang P, Jiang Q, Li B, Liu T, Li X, Chen G, et al. Ultra-low frequency oscillation analysis considering thermal-hydro power proportion. Int J Electr Power Energy Syst 2023;148:108919.

[4] Zhang Y, Wiese N, Liu Z, Braun M. On the control interaction of synchronous machine and inverter-based resources during system-split situations. Int J Electr Power Energy Syst 2023;152(June):109227. https://doi.org/10.1016/j.ijepes.2023.109227.

[5] Li J, Wei Y, Li X, Lu C, Guo Xu, Lin Y, et al. International Journal of Electrical Power and Energy Systems Modeling and stability prediction for the static-power-converters interfaced flexible AC traction power supply system with power sharing scheme. Int J Electr Power Energy Syst 2023;154:109401.

[6] Costa NE, Revel G, Alonso DM, Fernández RD. Detection of the stability boundary associated to subsynchronous oscillations in DFIG based wind farms. Int J Electr Power Energy Syst 2023;146:108783.

[7] Shair J, Zhan Y, Wang L, Xie X. International Journal of Electrical Power and Energy Systems Impedance network-based oscillatory stability analyzer (INOSA) – A frequency domain tool for investigating IBR-grid interactions. Int J Electr Power Energy Syst 2024;155(PA):109480. https://doi.org/10.1016/j.ijepes.2023.109480.

[8] Meng Z, Xu H, Ge P, Hu J. Large-signal modeling and stable region estimation of DC microgrid with virtual DC machine control. Int J Electr Power Energy Syst 2023;151(February):109122. https://doi.org/10.1016/j.ijepes.2023.109122.

[9] Mateu-Barriendos E, Cheah-Mane M, Prieto-Araujo E, Mehrjerdi H, Gomis-Bellmunt O. Oscillatory frequency characterization based on impedance analysis. Int J Electr Power Energy Syst 2023;152(May):109208. https://doi.org/10.1016/j.ijepes.2023.109208.

[10] Wang Y, Xu Y, Tao S, Peyghami S, Blaabjerg F. A modified modal sensitivity method for resonance analysis in power electronic systems. Int J Electr Power Energy Syst 2023;147:108866.

[11] Wu M, Zeng J, Ying G, Liu J. A d-axis current error compensation method based on coupling mechanism for Grid-Connected inverters under weak grid. Int J Electr Power Energy Syst 2023;151:109189.

[12] Tao R, Wu M, Ying G, Tang J, An R, Wang Q, et al. A phase compensation method combined with power correction for suppressing sub-synchronous resonance of wind generation under weak grid. Int J Electr Power Energy Syst 2023;151:109115.

[13] Li G, Pan H, Liu X, Yin L, Hwang Goh H. PLL phase margin design and analysis for mitigating sub/super-synchronous oscillation of grid-connected inverter under weak grid. Int J Electr Power Energy Syst 2023;151(March):109124. https://doi.org/10.1016/j.ijepes.2023.109124.

[14] Nafiz Musarrat M, Fekih A. Event-Triggered robust control scheme for sub-synchronous resonance mitigation in DFIG-based WECS. Int J Electr Power Energy Syst 2023;148(February):109006. https://doi.org/10.1016/j.ijepes.2023.109006.

[15] Ahmed M, Alsokhiry F, Ahmed KH, Samy Abdel-Khalik A, Al-Turki Y. Robust damping and decoupling controller for interconnected power network based on distributed energy resources. Int J Electr Power Energy Syst 2023;145:108581.

[16] Yang S, Liu K, Qin L, Zhu S, Xu Bo, Wang Q. A broadband active damping method for high-frequency resonance suppression in MMC-HVDC system. Int J Electr Power Energy Syst 2023;146:108791.

[17] Guan L, Yao J. Dynamic stability improvement scheme for dual-sequence PLLs in VSC based renewable energy generation system during asymmetrical LVRT. Int J Electr Power Energy Syst 2023;145:108683.

[18] Vule Y, Kuperman A. Plug-in disturbance observer assisted DC link voltage control of grid-connected converters to improve transient performance without deteriorating grid current quality. Int J Electr Power Energy Syst 2022;143(April):108439. https://doi.org/10.1016/j.ijepes.2022.108439.