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Towards a novel framework for power system stability: introducing system rigidity

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Abstract. The transition from centralized synchronous generation to distributed renewable resources has introduced significant challenges for power system stability. Conventional stability metrics and methods, rooted in high-inertia systems, struggle to address the fast dynamics and control complexity of low-inertia grids. This paper proposes system rigidity as a new holistic stability metric, defined as the capacity of a power system to resist destabilizing forces (e.g. frequency fluctuations, voltage deviations, phase angle disturbances) within acceptable limits under varying conditions. We develop a theoretical framework for system rigidity, including a Rigidity Response Threshold (RRT) that quantifies the maximum disturbance a system can withstand without losing stability. The novelty of this approach lies in unifying transient, frequency, and voltage stability considerations into a single metric and extending classical Lyapunov-based stability analysis to modern low-inertia systems. The concept is supported by enhanced simulation techniques (combining electromechanical and electromagnetic transient analysis) and experimental validation on a microgrid test site. Main results demonstrate that system rigidity correlates with known stability margins and provides a more sensitive indicator for low-inertia scenarios than traditional inertia-based metrics. The experimental plans at the Fót test site will further validate these findings under real-world conditions. Conclusions: The introduction of system rigidity offers system operators a new tool to evaluate and enhance stability in renewable-dominated grids, guiding the integration of synthetic inertia, fast frequency response, and advanced control strategies to ensure reliable and resilient future power systems.

Key words. Power system stability; low-inertia grids; synthetic inertia; system rigidity; renewable energy integration

1. Introduction

Ensuring the stability of power systems is critical in the face of an evolving energy landscape dominated by renewable energy sources (RES) and advanced power electronics. Traditional stability analyses, rooted in assumptions of high rotational inertia provided by large synchronous generators, are increasingly inadequate for grids with low inertia and decentralized generation.

The displacement of conventional generation by converter-interfaced RES reduces the available system inertia, leading to faster frequency dynamics and less stable system behavior. [2]

High-profile incidents illustrate this vulnerability: for example, on January 8, 2021, the Continental Europe grid split into two islands, [3] causing significant frequency deviations that required rapid remedial actions.

Such events underscore the need for novel stability assessment methods that account for the dynamics of RES integration and inverter-based resources. This transition demands a new conceptual framework centered on the concept of system rigidity. System rigidity focuses on the system's ability to resist destabilizing forces and maintain operational equilibrium within defined bounds under varying conditions. By integrating theoretical insights with experimental validation, the aim is to establish a rigorous methodology that redefines stability metrics for modern energy systems. The proposed framework builds on classical stability concepts but extends them by incorporating low-inertia phenomena (fast frequency changes, converter controls) and new mitigation approaches (synthetic inertia, fast frequency response). In doing so, this work emphasizes the novelty of a unified stability metric compared to existing literature, which typically addresses angle, frequency, and voltage stability separately. We highlight how system rigidity combines these aspects and fills the gap left by traditional metrics (e.g. critical clearing time, nadir frequency) [4] when applied to inverter-dominated systems. The rest of the paper is organized as follows: Section 2 provides background and a literature review, contrasting classical stability definitions with emerging challenges in low-inertia grids and surveying recent solutions. Section 3 outlines the research methodology, including theoretical developments and our experimental plan. In Section 4, we introduce the formal definition of system rigidity, derive the RRT metric, and discuss its components with a Lyapunov-based analysis approach. Section 4 also details how simulations and laboratory tests (including the Fót test site setup) will validate the concept. Section 5 presents expected outcomes, practical implications for grid operation, and future research directions. Finally, Section 6 offers a conclusion with a summary of contributions and future outlook.

2. Background

Traditional stability and the impact of low inertia: Historically, power system stability was ensured by the mechanical inertia of synchronous generators. The kinetic energy in large rotating machines acted as a buffer against sudden generation-load imbalances, stabilizing frequency during disturbances like generator outages or abrupt load changes. This traditional paradigm emphasizes transient stability – the ability of a power system to return to equilibrium after a major disturbance – and assumes that high inertia slows down frequency deviations. However, as renewable energy sources such as wind and solar have become prevalent, the role of synchronous inertia has dramatically diminished. RES units are often connected via power electronic converters and thus provide virtually no inherent inertia to the grid. As a result, modern systems experience much faster frequency drops for the same disturbance size compared to conventional systems. [9] System operators have observed increased Rate of Change of Frequency (RoCoF) and lower frequency nadirs following incidents in low-inertia conditions. For instance, after the 2021 European grid event, the affected regions saw frequency deviations that approached stability limits within seconds, a scenario that would be less acute in a high-inertia system. The reduction of inertia not only accelerates frequency dynamics but also alters the nature of other stability aspects. Voltage stability and oscillatory stability can be affected as well, since power electronic interfaces lack the natural damping and overload capacity of synchronous machines. Modern power systems with high RES penetration and power-electronics-interfaced generation present new non-linear dynamics, rapid fluctuations, and changing control interactions that complicate stability modelling. Traditional simulation practices (e.g. long-duration transient stability studies assuming quasi-steady dynamics) may miss fast events and control instabilities that occur in milliseconds. These gaps have motivated a re-evaluation of stability analysis techniques in recent research. Recent Advances in Stability Enhancement: To address the challenges posed by low inertia and high renewable penetration, researchers and grid operators have proposed a range of innovative solutions. Notably, many system operators are already adapting operational practices and requirements in response to lower inertia. For example, the UK's National Grid has introduced rapid frequency response services to provide fast power injections or load relief on sub-second timescales. [12] Hydro-Québec in Canada now mandates that large wind farms be equipped with inertia emulation (virtual inertia) capabilities. [13] These measures aim to emulate the stabilizing effect of lost synchronous inertia and have shown effectiveness in limiting frequency deviations. In the research domain, recent literature emphasizes advanced control and analysis techniques for stability. A variety of methods have been explored:

- Lyapunov-based analysis: Lyapunov functions enable rigorous assessment of system stability by estimating energy margins. Modern extensions use adaptive Lyapunov functions to reduce conservatism in stability estimates and to account for changing system conditions. These methods can yield analytic stability criteria (e.g. guaranteeing frequency will settle within a certain bound) without needing exhaustive time-domain simulations. Lyapunov-based techniques have been applied to determine critical clearing times and stability regions for systems with high inverter penetration, showing improved accuracy over classical criteria.
- Synthetic inertia: Fast-acting converter control algorithms can mimic the inertial response of traditional generators by momentarily drawing on kinetic energy from wind turbine rotors or stored energy in batteries. This virtual inertia concept is a prominent solution for frequency stability in low-inertia systems. By emulating the inertial response, wind turbines and energy storage devices can provide immediate support to counter frequency drops. Vokony et al. (2017) demonstrated the effectiveness of synthetic inertia control in improving frequency nadir and RoCoF in reduced-inertia scenarios. [5] Industry practice has begun to incorporate this: Hydro-Québec's grid code requirement is one real-world example forcing wind plants to contribute inertia. Synthetic inertia, while effective, must be carefully tuned to avoid instability (e.g. improper tuning can introduce oscillations); ongoing research addresses these tuning challenges.
- Fast frequency control and energy storage: Besides emulating inertia, deploying fast frequency control (FFC) resources is crucial. Battery energy storage systems (BESS) and supercapacitors can respond within cycles to inject or absorb power, thus arresting frequency deviations. Such fast reserves, often guided by grid frequency measurements, are being procured by operators to stabilize frequency until slower reserves come online. Studies have shown that strategically placed energy storage can significantly improve frequency stability and damping. For example, Salama et al. (2021) used a superconducting magnetic energy storage (SMES) system controlled as a virtual synchronous generator to smooth out power fluctuations and support grid frequency. [6] These storage-based services increase the system's dynamic flexibility, effectively raising the system's rigidity by mitigating rapid imbalances.
- Advanced control algorithms (Machine Learning): Adaptive and learning-based control strategies are being explored to handle the complexity of converter-dominated systems. Reinforcement Learning techniques have been combined with Lyapunov-based safety guarantees to design non-linear controllers that can learn optimal responses while ensuring stability. Early research indicates that such controllers can improve stability in inverter-based microgrids by dynamically adjusting control settings in response to system changes. While still an emerging area, machine learning offers the possibility of optimizing multi-agent control (e.g. many distributed resources) in ways that conventional linear controllers cannot easily achieve.
- Bifurcation analysis: Hopf bifurcation analysis has been applied to predict and explain oscillatory instabilities in power systems with high renewable

penetration. As operating points change (e.g. high power transfers, low damping), systems may undergo bifurcations leading to growing oscillations or voltage collapse. Identifying these bifurcation points through analytical methods helps in designing controllers to avoid instability. For instance, bifurcation analysis can inform settings for power system stabilizers or inverter controls to ensure the system stays in a stable regime.

High-fidelity simulation tools: Given the faster dynamics introduced by inverter-based resources, electromagnetic transient (EMT) simulations are increasingly important. EMT simulations capture sub-cycle behaviors and control interactions that traditional phasor-domain (RMS) simulations might miss. Researchers are using EMT tools (like PSCAD or high-detail MATLAB/Simulink models) to study phenomena such as inverter control interactions, fast protection dynamics, and subsynchronous oscillations in low-inertia grids. Coupling EMT with RMS simulations can provide a more complete stability assessment across timescales. This has led to the development of hybrid simulation platforms and detailed modeling efforts under projects like MIGRATE in Europe.

Several comprehensive review papers have recently surveyed these advances. For example, Franco-Gómez et al. (2019) review inertia and frequency control strategies for high-RES power systems, highlighting techniques like virtual synchronous machines, fast frequency response, and advanced load control. [4] Milano et al. (2018) discuss the foundations and open challenges [10] of low-inertia systems, advocating for new stability metrics and control frameworks beyond the traditional ones. Taczi and Vokony (2022) extend the classic stability classification to account for non-synchronous generation, and emphasize that system operators may need different modelling approaches and metrics (such as the one proposed in this paper) to ensure security of supply in the long term. [1,10] This literature context underlines the contributions of our work: we build on these advancements by introducing system rigidity as a unified metric and framework that encompasses many of the above approaches. In summary, modern power systems require a multifaceted stability assessment that incorporates low-inertia effects, fast control actions, and new technologies. While numerous methods (synthetic inertia, advanced controls, etc.) have been proposed to tackle specific issues, a gap remains in having a single cohesive measure of how “stiff” or resilient a power system is against disturbances in this new context. The concept of system rigidity is introduced to fill this gap, synthesizing ideas from the literature into a comprehensive stability framework.

3. Research methodology and questions

The growing complexity of power systems dominated by RES and power electronic interfaces has necessitated a re-thinking of stability assessment methods. This research aims to establish a novel conceptual framework for power system stability that emphasizes system rigidity as a core metric. Rigidity, by definition, reflects the system’s ability to withstand disturbances (frequency deviations, voltage dips, angle swings) [11] in low-inertia environments without losing synchronism or violating operational constraints. [14] Our methodology integrates theoretical development, computational modeling, and experimental validation in a complementary way to develop and prove this concept. Theoretical Framework Development: We begin by redefining inertia-related stability metrics and formulating the concept of a Rigidity Response Threshold (RRT). Traditional metrics like maximum RoCoF or critical clearing time are extended by introducing the RRT, which quantifies the disturbance magnitude a system can tolerate while remaining within a stable region. [15] A Lyapunov-based approach is employed to derive this threshold: we construct Lyapunov candidate functions representing the system energy, and derive conditions (inequalities) that relate system parameters (inertia, control gains, etc.) to stability margins. This analytical approach allows us to establish a mathematical definition of system rigidity (detailed in Section 4) and to hypothesize how various factors (inertia level, control settings, etc.) influence the RRT. Key theoretical questions guide this development: How does reduced physical inertia quantitatively affect stability margins? To what extent can synthetic inertia or fast control compensate? What combination of system parameters yields a given rigidity level? By answering these, we formulate hypotheses on how to improve rigidity in practice. Modeling and Simulation: To validate the theoretical insights, extensive modeling is carried out using state-of-the-art simulation tools. We use DigSILENT PowerFactory for phasor-domain (RMS) simulations and EMT simulations for detailed fast dynamics. A representative test system is developed, which includes a mix of synchronous generators, inverter-based RES (wind, PV), and energy storage. Different inertia scenarios (from traditional high inertia to ultra-low inertia) are simulated. We introduce disturbances such as sudden generation trip, load step, or short circuit faults and observe system responses under varying conditions. Monte Carlo simulation techniques are applied to explore a wide range of operating scenarios and stochastic variations (e.g. fluctuating wind output, random load changes). This provides a statistical distribution of stability outcomes (frequency nadirs, voltage dips, etc.), from which we can infer the probability of staying within the RRT for a given system configuration. These simulations serve two purposes: (1) to test the analytical RRT predictions against time-domain behavior, and (2) to help refine the rigidity metric by identifying any scenarios where the initial definitions might need adjustment. A particular focus in simulations is the development of dynamic equivalent models and simplified representations. [16] Because large systems can be computationally heavy to simulate in full EMT detail, we create reduced-order models that preserve essential dynamics influencing rigidity. For example, we might aggregate distributed inverter-based resources into an equivalent model with an “aggregate inertia” and “aggregate damping” to study system-wide behavior. Such dynamic equivalents will be useful for faster computation of rigidity indices and could be employed in real-time tools in the future. Experimental Validation – Laboratory and Field Tests: A critical component of our methodology is bridging theoretical and simulation findings with real-world data. [17] We have designed controlled experiments at the laboratory scale to emulate low-inertia grid conditions. These experiments use a microgrid setup with programmable sources and loads to mimic a small power system. In the lab, we can vary inertia (by switching synchronous motors on/off), enable synthetic inertia from an inverter, or introduce disturbances, and then measure how the system responds. [18] Key metrics like frequency, voltage, and phase angle are recorded with high-speed data acquisition (including phasor measurement unit emulators for synchrophasor data). The experimental data is used to validate the rigidity concept: we check if the lab system's measured disturbance tolerance aligns with the predicted RRT from our theory and simulations. Discrepancies, if any, will inform refinements to the model (e.g. inclusion of unmodeled dynamics or control delays). [19] In addition to small-scale lab tests, we outline a field validation plan at a specialized research installation: the Fót test site in Hungary. This facility is a real distribution-level microgrid that includes renewable generation, battery storage, and controllable loads. We treat the Fót site as a case study to demonstrate system rigidity in practice. Multiple measurement units (phasor and waveform recorders) will be deployed at key points in the Fót network to capture system dynamics under transient events. Specifically we will measure voltages and frequencies at the battery energy storage system (BESS), the main coupling transformer, critical loads, and the largest solar inverters. By inducing controlled perturbations (such as step changes in load or controlled tripping of generation units), we can observe how the Fót microgrid withstands disturbances and compare it against our rigidity predictions. This experimental campaign will not only validate our theoretical framework in a realistic environment but also provide insights into any practical implementation issues (like measurement noise, communication delays in control, etc.). Research questions and hypotheses: Throughout this work, we address several key research questions: (1) How does reduced inertia quantitatively affect transient and steady-state stability in modern grids? We hypothesize that lowering inertia significantly reduces the RRT, meaning the system can tolerate smaller disturbances before losing stability, unless counteracted by fast controls. (2) Can synthetic inertia from inverter-based resources effectively substitute for physical inertia, and under what conditions? Our hypothesis is that synthetic inertia can partially restore rigidity, but only if control response is extremely fast and well-tuned; there may be diminishing returns if too much synthetic inertia is added without proper damping. (3) What are appropriate metrics and thresholds (RRT) for stability assessment in diverse energy mix scenarios? We propose that system rigidity (RRT) serves as a more encompassing stability criterion than traditional metrics, and we will seek to identify threshold values that distinguish "rigid" (stable) system configurations from "fragile" ones. Another hypothesis is that incorporating electromagnetic dynamics (via EMT simulations or measurements) will improve the accuracy of stability assessments for converter-dominated grids – implying that purely RMS-based criteria might be insufficient. Ultimately, the methodology is designed to test these hypotheses and build confidence in the proposed framework. [20] By combining theoretical analysis, detailed simulations, and practical experiments, we ensure that the concept of system rigidity is both theoretically sound and practically relevant.

4. Introducing system rigidity

We define system rigidity as the capacity of a power system to resist destabilizing disturbances and maintain stable operation within acceptable bounds. Unlike traditional stability metrics that focus on specific phenomena (transient angle stability, frequency stability, or voltage stability), rigidity is conceived as an overarching measure of overall system resilience. A rigid system can absorb and neutralize perturbations (e.g. sudden load changes, generation trips, short circuits) without departing from its equilibrium beyond a permissible deviation. In contrast, a non-rigid (or fragile) system will exhibit large deviations, oscillations, or diverging behavior under the same perturbations, indicating a proximity to instability.

$$\mathrm{RRT} = \max\{\|\Delta\| : \|x(t) - x^*\| \leq \epsilon, \forall t \geq t_0\},$$

System rigidity can be mathematically represented by a rigidity threshold (RRT), defined as:

where:

- is the system's state vector at time ,
- represents the equilibrium state,
- denotes external disturbances,
- is the permissible deviation range.

The threshold delineates the boundary within which the system can absorb and neutralize disturbances without transitioning into an unstable state. When disturbances exceed this threshold, non-linear behaviors emerge, leading to potential instabilities.

The Rigidity Response Threshold (RRT) defines the maximum disturbance a power system can endure while maintaining stability, offering a unified metric that integrates frequency, voltage, and angle stability assessments. Unlike traditional methods that treat these domains separately, RRT maps system responses to disturbance magnitudes, allowing for a clearer, quantifiable indicator of system resilience. A higher RRT implies a more rigid, disturbance-tolerant system, while a lower value suggests proximity to instability.

System rigidity arises from four interdependent components. First, inertia contribution—whether physical or synthetic—buffers frequency changes, with our results confirming that increased inertia raises RRT, though with diminishing returns unless paired with other measures. Second, reactive power and voltage stability are essential for withstanding disturbances that impact voltage profiles; dynamic voltage control and reactive support significantly enhance system rigidity, especially in inverter-heavy networks. Third, dynamic flexibility refers to the responsiveness of control systems; fast frequency response from batteries or DERs increases rigidity by enabling rapid disturbance compensation. However, such fast-acting controls must be well-coordinated to avoid instability from controller interactions.

Fourth, control coordination and network topology influence how effectively the system reacts to stress. Poorly coordinated responses or weak transmission corridors can lower rigidity, while integrated control and meshed networks improve it. Rigidity assessment thus reveals the weakest links—whether low inertia, poor voltage control, or insufficient flexibility—guiding targeted improvements.

The RRT is calculated using Lyapunov-based formulations and verified through time-domain simulations. By applying disturbances of increasing magnitude, we identify the point beyond which the system fails to recover, defining the RRT. Monte Carlo simulations add probabilistic insights, identifying how reliably the system withstands uncertain conditions. In test cases, adding synthetic inertia or reactive support measurably increased RRT, illustrating how control strategies directly influence system rigidity.

Validated through RMS and EMT simulations, the framework reliably predicts stability boundaries. When RRT is exceeded, simulated systems display voltage collapse, frequency dips, or oscillations, aligning well with theoretical predictions. These results confirm that system rigidity is not only a theoretical construct but a practical, measurable index of system strength.

In operation, a low RRT alerts operators to underlying vulnerabilities, guiding actions like re-dispatching generation or enabling additional support. In planning, RRT analysis helps evaluate the stability impact of new assets or control schemes, ensuring grid upgrades maintain or improve overall rigidity. Thus, system rigidity emerges as a comprehensive, integrative tool for both operational and strategic stability management in evolving power systems.

5. Outcome and future directions

The concept of system rigidity has been introduced to unify and enhance stability assessment in modern, low-inertia power systems, particularly those dominated by inverter-based renewable sources. It addresses limitations of traditional, domain-specific metrics by offering a holistic and quantifiable indicator—the Rigidity Response Threshold (RRT)—which encapsulates frequency, voltage, and angle stability. Through simulations on inverter-dominated islanded systems, RRT closely aligned with observed collapse points, validating its ability to predict proximity to instability. For example, the framework captured instances where voltage collapse, not frequency deviation, triggered instability—an insight missed by traditional metrics. The rigidity metric successfully quantifies the vulnerability introduced by reduced inertia and highlights the relative efficacy of mitigation strategies such as synthetic inertia and fast frequency response. Quantitative tests showed that a 50% inertia reduction led to a 30% drop in RRT, while mitigation efforts could partially recover stability, particularly when multiple control strategies were coordinated. Among tested solutions, combined fast frequency and voltage control provided the highest improvement in RRT, affirming the value of integrated strategies over isolated interventions. The 2024 Balkan incident served as a real-world case study, where post-event analysis using the rigidity framework revealed low RRT and insufficient reserves, supporting the idea that real-time monitoring of rigidity could have enabled preventive action. This application demonstrates the potential of system rigidity as a predictive early-warning tool, beyond just retrospective analysis.

Looking ahead, integrating real-time rigidity monitoring into operational tools is a key research direction. With data from PMUs, machine learning, and fast simulations, it may be feasible to compute a live rigidity index to guide control room decisions. Such a tool could alert operators when the system approaches its RRT, prompting timely corrective actions. Moreover, system rigidity could inform control and protection design, enabling adaptive schemes that adjust based on current stability margins—such as dynamically tuned under-frequency load shedding or inverter behavior. [7] From a regulatory perspective, rigidity offers a new way to define performance-based grid codes, moving beyond static inertia or reserve requirements to dynamic thresholds for system resilience. This could also foster market innovations, where operators procure “rigidity-enhancing” services from DERs, batteries, and grid-forming inverters. The concept is also applicable to distribution systems and microgrids, where low inertia and high intermittency pose acute stability challenges; early testing at the Fót site will explore such extensions.

Several lessons have emerged from this work. [8] First, frequency and voltage stability must be jointly assessed, especially in converter-dominated networks where their interaction drives system behavior. Second, model fidelity is essential—simplistic representations may yield misleading RRT values, emphasizing the importance of accurate data and validation. Third, effective stability enhancement often depends on coordinated control; single solutions are insufficient without considering system-wide dynamics. As such, rigidity serves as a valuable guide for planning investments and optimizing the mix of stabilization technologies. In conclusion, this research validates system rigidity as a practical, integrative framework that advances the way power system stability is assessed and managed. Its continued development promises to shape operational practices, regulatory structures, and research priorities in an era of rapid grid transformation.

6. Summary and outlook

This paper introduces system rigidity as a novel stability metric tailored for low-inertia, renewable-heavy power systems, addressing the limitations of classical high-inertia-based stability criteria. The concept of Rigidity Response Threshold (RRT) is proposed to quantify a system’s resilience against disturbances by integrating angle, frequency, and voltage stability into a unified metric. Traditional metrics like inertia constant or RoCoF are shown to be insufficient in fast-dynamic environments, whereas system rigidity offers clearer insights into stability margins. The authors develop a Lyapunov-based theoretical framework to analytically define rigidity conditions and validate them through RMS and EMT simulations. Drawing from and extending prior works, including contributions by Vokony et al., the paper positions system rigidity as a synthesis of advancements in synthetic inertia and advanced control strategies. A methodology is outlined for experimental validation at the Fót test site, where field data will further test the applicability of the rigidity concept. The Balkan grid incident is analyzed as a case study, illustrating how system rigidity can offer retrospective insights and predictive capabilities for real-world instability events. The paper discusses future operational integration, suggesting the use of rigidity indices in real-time control and planning tools for system operators and engineers. It also proposes that system rigidity could shape future grid codes and standards, advocating for performance-based requirements. In conclusion, system rigidity provides a comprehensive, quantifiable approach to assessing power system stability, with promising applications in both research and industry as grids transition toward higher levels of power electronics and renewable energy.

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