23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)
Tenerife (Spain), 25th to 27th June 20245
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.23, September 2025

Time domain assessment of power system stability in case of high share of non-synchronous generation – limitation analysis of electromechanical transient simulations

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Abstract. The transition from centralized synchronous generation to distributed renewable energy sources has introduced significant challenges to power system dynamics and stability. This shift disrupts traditional assumptions in modelling methodologies and calls for a re-evaluation of simulation practices. Power system frequency stability is widely analysed through time domain electromechanical transient simulation, where the electrical frequency is calculated by the swing equation. However, with the growing share of converter-based, non-synchronous generation, this approach becomes problematic, as the electromechanical description can only be applied to certain parts of the generation portfolio. Electromagnetic transient simulation covers the timespan of such transients, however require more complex modelling techniques. This paper explores the limitations of the classical electromechanical transient stability analysis by simulation studies, while also discussing key research advancements in the field and shows simulation results of the discussed methods for frequency stability analysis.

Key words. Power system stability, electromechanical transient, non-synchronous generation

1. Introduction

The increasing integration of renewable energy sources into power systems has fundamentally altered the nature of power generation, transitioning from a centralized, synchronous paradigm to a more distributed, non-synchronous one. Traditionally, power system stability analyses have relied on well-established modelling techniques grounded in the physics of synchronous machines. The classical electromechanical transient simulation, based on the swing equation, has been the foundation for analysing frequency stability and dynamic responses in conventional power systems [1]. However, with the rapid expansion of converter-based generation, such as wind turbines and photovoltaic systems, these traditional methods face limitations that must be addressed properly, with accurate, validated dynamic models [2].
The shift from synchronous to non-synchronous generation challenges fundamental assumptions in power system analysis. In conventional power grids dominated by synchronous generators, frequency stability is governed by the inertia provided by the rotating masses of synchronous machines. This natural inertial response mitigates frequency deviations following disturbances. However, non-synchronous generation, primarily interfaced through power electronic converters, lacks this direct electromechanical coupling, resulting in a power system with reduced inertia. This shift has introduced new dynamics that are not adequately captured by conventional time-domain simulations. While electromechanical transient simulation (usually referred as root mean square (RMS) studies) remains suitable for capturing system-wide frequency dynamics in high-inertia systems, its applicability diminishes as the share of non-synchronous generation increases. This is because the assumptions behind the swing equation and classical stability models do not hold for inverter-based resources, which operate with fundamentally different control dynamics. Instead, electromagnetic transient (EMT) simulation techniques provide a more accurate representation of fast transients associated with power electronics, but they come with increased computational complexity and modelling challenges.
Given the limitations of conventional electromechanical transient simulation methods and the complexity of full-scale EMT simulations, there is a need for novel analytical methodologies that can bridge the gap between these approaches. This paper aims to explore the implications of non-synchronous generation on power system dynamics, highlighting the challenges posed by fast transients and evaluating alternative modelling and simulation techniques. By understanding these emerging dynamics, we can develop more effective stability assessment tools that account for the evolving nature of modern power systems.
The paper is organized as follows. Chapter 2 covers the theoretical background of frequency and transient stability assessment, while Chapter 3 focuses on the methodological overview. Chapter 4 provides simulation result-based discussion of RMS and EMT simulations, while Chapter 5 summarizes the conclusions of the paper.

2. Theoretical background

Stability analysis has evolved significantly, particularly in defining time constants associated with different stability phenomena. The IEEE/CIGRÉ Joint Task Force on Stability Terms and Definitions, led by P. Kundur et al. (2004) [1], introduced a comprehensive classification of power system stability into rotor angle stability, frequency stability, and voltage stability. Each category was associated with specific time constants:

- Transient stability occurs within 0.1–10 seconds, capturing large disturbances and generator rotor angle dynamics.
- Small-signal stability involves oscillations with time constants ranging from fractions of a second to several seconds.
- Frequency stability spans from milliseconds (inertia response) to minutes (secondary control and load response).
- Voltage stability varies widely, with fast dynamics (milliseconds to seconds) driven by power electronics and slower dynamics (minutes to hours) linked to load restoration and reactive power support.

This classification is widely considered as the classical stability assessment in power systems. The electromechanical nature of synchronous generators is especially important in transient stability, and frequency stability studies. With presence of large scale of non-synchronous generation, there are deficiencies in these classical methods. In 2021, a working group led by N. Hatziargyriou et al. [3] revisited and extended these classifications to reflect the growing presence of converter-based resources. The updated framework emphasized:

- Electromagnetic transients (microseconds to milliseconds) affecting power electronic interfaces.
- Fast electromechanical transients (milliseconds to seconds) driven by inverter control strategies.
- Mid-term and long-term stability (seconds to hours) incorporating interactions between traditional and non-synchronous generation.

Beside the timeframes, two new categories – resonant and converter stability, namely – were proposed to cover the dynamics of modern power systems with high share of non-synchronous, renewable power generation. This evolution underscores the necessity of new simulation techniques that accommodate the different time constants governing modern power system dynamics. Power electronic converters introduce fast transient phenomena that differ significantly from the slower electromechanical transients observed in synchronous machines. Unlike traditional generators, which respond to disturbances with a combination of inertial, governor, and damping effects, converter-based resources exhibit rapid control-driven responses dictated by their internal phase-locked loops (PLLs) and current controllers. These fast transients occur on sub-cycle timescales and can lead to interactions between grid-following and grid-forming inverters, affecting system stability in unforeseen ways.

Furthermore, the absence of direct coupling between electrical and mechanical dynamics in non-synchronous generation alters the fundamental behaviour of power system frequency. The response of power electronic converters depends on pre-programmed control schemes, which do not inherently provide the same frequency support as synchronous machines. This can result in increased frequency volatility, reduced damping, and potential instability under fault conditions or sudden changes in load and generation.

3. Methodological overview

Root-Mean-Square (RMS) and Electromagnetic Transient (EMT) simulation methods represent two fundamental approaches for analysing power system dynamics, each with distinct mathematical formulations, simplifications, and boundaries of application. RMS simulations, also referred to as phasor-domain simulations, are based on the fundamental frequency approximation, where voltage and current waveforms are represented as slowly varying phasors rather than instantaneous time-domain signals. This allows for a substantial reduction in computational complexity, making RMS simulations particularly suitable for large-scale power system studies over extended time horizons. Mathematically, RMS models rely on the swing equation to describe rotor angle dynamics. Frequency stability in RMS simulations is evaluated through quasi-static frequency deviations derived from power imbalances, typically relying on simplified frequency response models. However, due to the fundamental frequency assumption, RMS simulations are limited in capturing sub-cycle transients and fast control interactions, making them less suitable for studying the rapid response of inverter-based resources.

To address the challenges posed by the growing penetration of inverter-based resources in power systems, various research efforts have been dedicated to developing methodologies that bridge the gap between root-mean-square (RMS) and electromagnetic transient (EMT) simulations. Traditional RMS models, while computationally efficient, often fail to capture the fast transients and control interactions characteristic of power electronic converters, whereas EMT simulations, though accurate, are computationally demanding and impractical for large-scale studies. Consequently, a range of hybrid modeling techniques, reduced-order models, and advanced co-simulation approaches have been proposed to balance accuracy and computational efficiency. By examining recent advancements, this section highlights key methodologies that enhance the representation of dynamic behaviours in mixed-inertia grids, ultimately improving the reliability and effectiveness of power system simulations.

Running an RMS simulation in a power system composed entirely of non-synchronous generation presents fundamental challenges due to the modelling assumptions inherent in RMS methods. RMS simulations rely on phasor-domain representations and the swing equation, which describe the electromechanical response of synchronous machines to disturbances. However, non-synchronous generation, does not possess physical rotational inertia or inherent frequency dynamics in the traditional sense. Instead, the response of these systems is governed by the control algorithms embedded within power electronic converters, which operate on much faster timescales than conventional electromechanical transients.

In an RMS simulation of a purely non-synchronous power system, several issues arise. First, without synchronous machines, the swing equation, which forms the foundation for frequency and angle stability studies, becomes invalid. The frequency of the system is no longer dictated by the electromechanical response of generators but rather by the control strategies implemented in grid-following and grid-forming inverters. Grid-following inverters rely on PLLs to track the system voltage phase angle, but these devices do not inherently define the system frequency, making it difficult to establish a stable frequency reference in an RMS simulation. Grid-forming inverters, on the other hand, can establish a voltage and frequency reference, but their dynamics are controlled by fast inner control loops that operate on sub-millisecond timescales, which are not captured adequately in RMS models. Another major limitation is the inability of RMS simulations to represent fast transients and control interactions between multiple inverters. Inverter control dynamics, such as droop control, virtual inertia emulation, and current-limiting behaviour during faults, occur on timescales ranging from microseconds to milliseconds. However, RMS models use simplified active and reactive power equations that do not capture these high-frequency transients. As a result, RMS simulations may produce unrealistic or misleading results when applied to a power system composed entirely of non-synchronous generators, failing to accurately reflect the stability characteristics of the system. Furthermore, the lack of inertia in a non-synchronous power system leads to very rapid frequency changes following disturbances, which RMS simulations are not designed to handle. In traditional RMS studies, frequency deviations evolve over seconds due to the inertia of synchronous machines, allowing for time-stepped numerical solutions to approximate system behaviour. In an inverter-based system, however, frequency variations can occur within milliseconds, requiring a more detailed representation of the control loops and power electronic switching dynamics.

In contrast to RMS, EMT simulations operate in the time domain and solve the full set of network equations without relying on phasor approximations. The governing equations include Kirchhoff's current and voltage laws applied to instantaneous voltage and current waveforms, which require numerical integration techniques such as the trapezoidal rule or backward differentiation methods. The mathematical formulation involves solving a large system of differential-algebraic equations at very small time steps, typically in the microsecond range, making EMT simulations highly accurate in capturing fast electromagnetic transients. Unlike RMS simulations, which primarily focus on electromechanical phenomena, EMT methods explicitly model the fast-switching behaviour of power electronic converters, including the dynamics of PLLs and inner current control loops. These features make EMT simulations essential for studying the transient response of non-synchronous generation, particularly in weak grids where rapid frequency and voltage variations occur. However, the high computational burden of EMT simulations limits their applicability to smaller network sections or shorter time frames.

EMT simulations may become necessary for assessing fast angle variations in systems dominated by grid-forming and grid-following inverters, where angle stability is dictated by control algorithms rather than mechanical inertia. Similarly, frequency stability studies using RMS simulations are appropriate when evaluating primary frequency control mechanisms over longer time frames, but they fail to capture sub-cycle frequency oscillations and interactions between multiple control loops in inverter-dominated systems. EMT simulations, on the other hand, provide a detailed representation of frequency dynamics at very short timescales, making them indispensable for analysing frequency instabilities driven by converter control interactions and fast transient disturbances. However current research focuses on the trade-off between the mentioned methods to provide practically applicable.

In [4], the authors conducted a detailed comparison between fundamental frequency positive sequence (RMS) and electromagnetic transient (EMT) simulation environments to assess the impact of inverter-based resources on protection schemes. compares RMS (PowerFactory) and EMT (PSCAD) simulation methods for analysing low-inertia power systems with significant converter-based wind generation. A two-area, four-machine test system incorporating wind farms was developed in both simulation environments, ensuring closely matched initial conditions. Tests involving short-circuit faults and load-step disturbances were performed. Results showed that while steady-state responses closely matched, transient differences arose due to RMS modelling limitations—particularly in capturing fast converter dynamics and fault ride-through behaviours. Thus, RMS simulations tended to underestimate transient challenges compared to EMT. The study provides a systematic approach for benchmarking these simulation methods, highlighting essential differences and RMS modelling constraints for accurately assessing stability in renewable-rich, low-inertia grids.

Authors in [5] compared different simulation models—specifically RMS and EMT models—for time-domain analysis of fault ride-through events in converter-interfaced distributed generation systems. The paper addresses the development and analysis of reduced-order models for voltage source converters by assessing their accuracy through the AC-side admittance in EMT and RMS simulation environments. Due to the detailed and computationally intensive nature of time-averaged EMT models, simplified models suitable for transient stability (RMS) analyses are required. The study systematically evaluates the impact of various simplifications—including inner current control, PLL, dead-time modelling, and AC/DC side dynamics—on the accuracy of the VSC models. It proposes four reduced-order models, each progressively simplified, and evaluates their validity and limitations across different frequency ranges.

Results indicate that significant model simplifications can compromise accuracy, particularly at higher frequencies.

Authors in [6] compare RMS and EMT simulation models for analysing short-term voltage stability of converter-interfaced distributed generation units during fault ride-through events. Three models were evaluated: a detailed EMT model, an average-value RMS model with complete converter control representation, and a simplified RMS model. The analysis focuses on symmetrical faults, assessing dynamic voltage and current behaviour and critical clearing times. Results indicate that while steady-state behaviour is closely matched, transient responses differ significantly, with RMS models slightly overestimating stability (higher critical clearing times) compared to EMT, especially in weak, inductive grids. Thus, the study recommends caution when applying simplified RMS models to voltage stability analysis in such conditions.

Authors in discusses key modelling limitations of RMS simulations in converter-dominated power systems compared to EMT simulations, introducing a new parameter called "Transient Voltage Difference" (ΔVCTR). It quantifies the error arising from the assumption of constant frequency and neglect of rapid electromagnetic transients in RMS modelling. Analytical derivation and numerical simulations reveal that RMS models significantly underestimate transient voltage responses and converter output voltage requirements, especially at smaller time steps critical for fast converter dynamics. This work highlights the boundary conditions under which RMS modelling becomes inadequate, emphasizing its limitations for accurately capturing dynamic responses in systems with high penetration of converter-based generation.

Kuri et al. [7] discussed key modelling limitations of RMS simulations in converter-dominated power systems compared to EMT simulations, introducing a new parameter called "Transient Voltage Difference". It quantifies the error arising from the assumption of constant frequency and neglect of rapid electromagnetic transients in RMS modelling. Analytical derivation and numerical simulations reveal that RMS models significantly underestimate transient voltage responses and converter output voltage requirements, especially at smaller time steps critical for fast converter dynamics. This work highlights the boundary conditions under which RMS modelling becomes inadequate, emphasizing its limitations for accurately capturing dynamic responses in systems with high penetration of converter-based generation.

Authors in [8] the limitations of RMS models for inverter-based resources from a small-signal stability perspective, specifically when compared to EMT models. The authors analyse grid-forming inverter models in a single-machine infinite bus setup, highlighting discrepancies in stability predictions between RMS and EMT models. RMS models, while computationally efficient, neglect higher-frequency dynamics and network frequency dependence, potentially missing critical dynamic phenomena. The study identifies conditions under which RMS modelling is insufficient, particularly in low reactance scenarios and when fast control dynamics are involved. It emphasizes careful tuning of model parameters and suggests verifying RMS results with EMT models when stability margins are low or when precise dynamic interactions must be captured.

Authors in [9] presented a benchmarking study comparing RMS and EMT wind power plant simulation models required by ERCOT. It identifies two key challenges: inherent simulation tool limitations (such as solver and timestep constraints) and simplifications needed in RMS models. The study tested various conditions including voltage and frequency disturbances and different system strengths (short-circuit ratios). Results showed good consistency between RMS and EMT models under typical operating conditions, but discrepancies arose under weaker grid conditions (low short-circuit ratios). To address these challenges, Vestas adopted a full-code integrated user-defined model approach, allowing identical parametrization and improved fidelity between RMS, EMT models, and real-world performance

These studies collectively underscore the importance of selecting appropriate modelling approaches—RMS versus EMT—based on the specific analysis requirements, particularly in the context of integrating inverter-based resources and ensuring effective protection and stability in modern power systems.

4. Comparative analysis: EMT vs. RMS in renewable-integrated systems

To demonstrate the differences between RMS and EMT simulation methodologies in the presence of non-synchronous generation, a comparative study was done using the IEEE 39-bus system in Digsilent PowerFactory 2023. This benchmark network, originally designed to represent a synchronous generator-dominated system, is adapted by progressively replacing conventional generators with inverter-based resources. The study aims to evaluate the limitations of RMS simulations in capturing the fast transients associated with power electronic converters and to highlight the necessity of EMT modelling for accurate dynamic analysis. Figure 1 depicts the topology of the demonstration network.

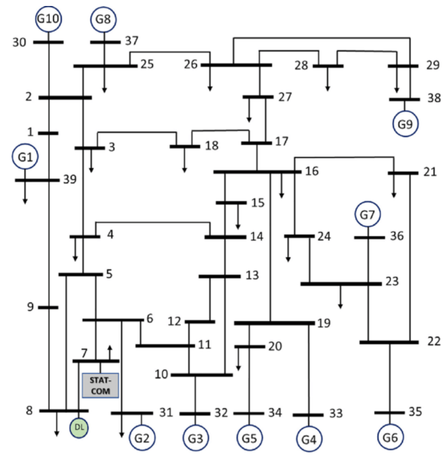

Fig. 1. Topology of the IEEE 39 Bus test network

Four different system configurations were examined to analyse the impact of non-synchronous generation on stability studies:

- Baseline Case (High-Inertia System) – The original IEEE 39-bus system, consisting of three synchronous generators, is simulated to establish a reference for dynamic behaviour under traditional electromechanical assumptions. 10 synchronous generators represent the generation mix, with 78 268 MWs kinetic energy.
- Different level of non-synchronous, grid following generation (5%, 20% and 30% of the total generation respectively) with the substation of G10, G9 and G8 in the model. With the 30% scenario, the kinetic energy decrease is around 10 000 MWs.

Each scenario is subjected to an identical disturbance, which is a load switching event that results in 100 MW instantaneous power change. The event happens at 1 s in each simulations, until that point the system is in steady state. The simulations are conducted in DIgSILENT PowerFactory, which allows both RMS and EMT analyses within the same platform. The network is modelled with detailed synchronous generator parameters, including governor and exciter dynamics for the conventional generation cases as per described in the PowerFactory example. The non-synchronous generators are represented using standard RMS models with simplified power flow equations and control blocks in phasor-domain simulations, whereas the EMT models incorporate detailed switching dynamics, phase-locked loop (PLL) behaviour, and inner control loops.

The performance indicator during the simulations was the centre of inertia (COI) frequency in per unit values. To avoid distortions caused by the frequency, generator speeds were exported from the simulations to calculate COI with weighing by the kinetic energy of each generator. With the replacement of each generator, the representation of COI also changes as the number of machines are decreasing. The COI per unit frequency was exported until 5 s to observe the transient, as the study was not aimed to analyse frequency control activities.

Figure 2 depicts the COI frequency per unit values from the RMS simulations. The effects of non-synchronous generation can be observed with the increasing rate of change of frequency and lower frequency nadir values.

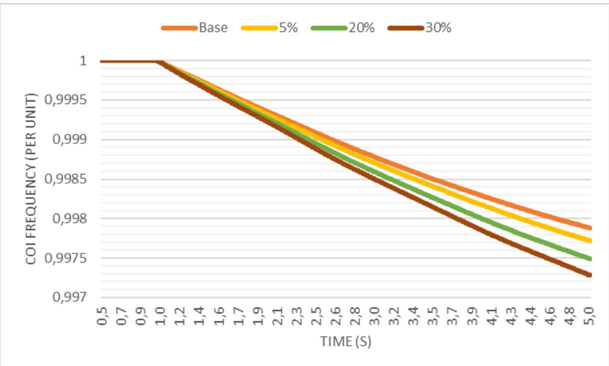

Fig. 2. COI frequencies with different renewable penetration levels

EMT simulations were performed in the same setting but from a different operation point. Only 2 scenarios were covered, the base case and the 5% ones. Figure 3 shows the COI frequency per unit results, where similar pattern is present: in the presence of non-synchronous generation the rate of change of frequency is slightly higher and the frequency nadir is slightly lower.

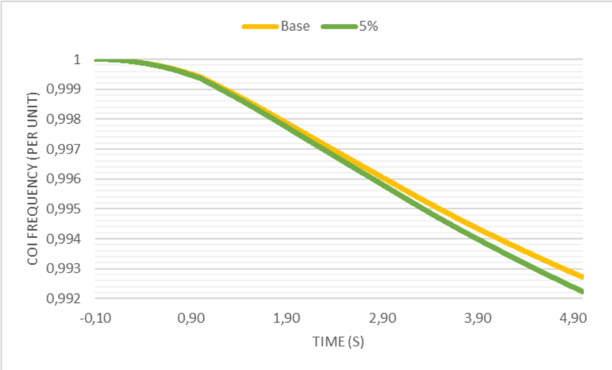

Fig. 3. COI frequency per unit values for two different scenarios in EMT simulation

Table I. summarizes the differences between the 5 s COI frequency per unit values. Even in such a simple setup there is a slight difference between RMS and EMT calculations, as the EMT calculated frequency value is lower. The difference is slightly lower than 1% in this study. However, the results are in line with the review results, the differences can be observed, and in some cases, it is expected that the transient value calculations would result in higher differences.

Table I. – COI frequency nadirs (per unit)

MIN COI frequency (p.u)	BASE	5%
RMS	**0,9934**	**0,9929**
EMT	**0,9927**	**0,9922**

The comparative simulations performed on the modified IEEE 39-bus system highlight several critical points regarding the validity and applicability of RMS and EMT methodologies. While RMS simulations clearly demonstrate their strengths in conventional high-inertia systems, the discrepancies observed when integrating converter-based resources emphasize their limitations. In scenarios with increasing shares of non-synchronous generation, the transient responses differ notably, particularly with regard to the initial rate of change of frequency and frequency nadir values.

Furthermore, the simulations underscore how even moderate shares of converter-interfaced generation significantly impact frequency stability metrics. This implies that traditional RMS studies may become increasingly insufficient without careful consideration of model validity and parameter tuning. Particularly, the smaller inertia contributions in the studied scenarios led to quicker and deeper frequency excursions, demonstrating the need for incorporating fast inverter dynamics more precisely within RMS models. Although the quantitative differences between RMS and EMT simulations were modest in this specific case, previous

research highlighted that such discrepancies become pronounced under weak grid conditions, fault scenarios, and more extensive converter-based penetration.
The demonstrated outcomes suggest that current RMS modelling methods may provide overly optimistic stability margins, potentially underestimating the severity of transients in highly non-synchronous grids. These findings are consistent with other recent benchmarking studies, reinforcing the recommendation that hybrid modelling techniques or advanced reduced-order EMT models may provide a viable balance between computational efficiency and accuracy. Future research could focus on validating such models across a broader set of scenarios, especially those involving faults, grid disturbances, and weak interconnections.

5. Conclusions

This study explores the challenges posed by the growing share of non-synchronous generation in power systems, emphasizing both a comprehensive review of stability assessment methodologies and a comparative simulation analysis. The review highlights the limitations of traditional RMS-based electromechanical transient simulations in accurately capturing the fast control-driven dynamics of inverter-based resources, underscoring the need for alternative modelling approaches. The evolving classification of stability phenomena, particularly with the introduction of resonant and converter stability concepts, reflects the necessity of rethinking traditional analysis techniques.
This study further emphasizes the necessity of re-evaluating traditional stability analysis methods to account for evolving dynamics in power systems dominated by non-synchronous, converter-based generation. The comparative analysis between RMS and EMT simulation environments reinforces existing evidence from the literature, highlighting the inherent limitations of RMS-based methods in accurately predicting dynamic behaviour in systems with substantial renewable penetration.
While RMS models remain valuable for system-level, long-term stability assessments due to their computational advantages, this study clearly indicates their constraints, particularly when transient phenomena and rapid inverter control interactions are involved. The minor differences observed in this paper should be viewed cautiously, as more significant discrepancies are likely under conditions of weaker system strength or higher inverter penetration.
Additionally, future work should address validation with real-world data from grids with high renewable integration to confirm the practical applicability. Enhanced modelling fidelity, through user-defined or advanced converter control representations, may further improve the accuracy of RMS models, providing critical insights into system behaviour without incurring prohibitive computational costs.
In conclusion, adapting simulation practices to the changing realities of power generation is essential for ensuring future grid reliability. The insights gained here contribute toward improving modelling accuracy, supporting better-informed operational and planning decisions in increasingly converter-dominated power systems.

Acknowledgement

István Vokony acknowledges the support of the Bolyai János Research Scholarship of the Hungarian Academy of Sciences (BO/50/24).

This publication was supported by the HYNET - this project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No. 101172757.

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