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Frequency and Angular Stability Assessment of An Evolved Dutch Power System under Hypothetical Dynamic Properties for 2050 Energy Transition

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***Abstract*—This paper presents a pivotal stability analysis of the Dutch power system within the context of increased renewable energy integration, employing multiple future scenarios to navigate the inherent uncertainties. A large-scale synthetic model, utilizing ENTSOE-E reference data, uses time-domain simulations and eigenvalue analysis to assess the influence of systemic inertia and kinetic energy on the power system's dynamic frequency and angular stability.**

The study identifies specific inertia and kinetic energy projections that could undermine the stability of the Dutch power system and potentially affect the continental European power system. It also discusses potential enhancements, including supplementary damping control, to improve the primary control functions of power electronics interfaced generation. The results highlight the critical need for power system planners and operators to take proactive steps to prevent instabilities, ensuring that renewable energy integration strengthens rather than compromises power system reliability.

***Index Terms*—power system stability, kinetic energy, inertia constants, frequency response, damping, energy transition**

I. Introduction

THE energy transition is reshaping power system operations and stability, presenting both an opportunity for significant advancement and a challenge for maintaining system integrity. The rise of Power Electronic Interfaced (PEI) generation, such as solar PV and wind, is transforming traditional stability mechanisms like inertia [1]. Systems with high shares of PEI generation are characterized by inherently lower levels of inertia, a fundamental aspect of power system stability [2].

This study utilizes ENTSO-E's broad spectrum of inertia projections for 2040, to illustrate the potential variability in future power systems [3], [4]. It integrates these projections with a large-scale synthetic model of the Dutch power system for 2050 to assess stability implications. Dynamic synchronous machine models, complete with control systems, emulate interconnections with neighboring power systems, facilitating a nuanced simulation of the Dutch power system's future state. This enables an in-depth analysis of how inertia and kinetic energy levels could influence stability as the system evolves.

The analysis focuses on frequency and angular stability under various disturbances, employing DIgSILENT PowerFactory v2024 SP2 for time-domain simulations and eigenanalysis. The study uses a synthetic model of the Dutch bulk generation, consumption, and transmission network created using publicly available information. This enables detailed analysis of stability phenomena affected by inertia and kinetic energy uncertainties including coupling of phenomena.

Numerical and graphical results provide valuable insights for system planners and operators regarding potential dynamic performance and mitigation strategies. While essential for sustainability, the energy transition poses complex stability challenges, necessitating a thorough understanding to develop effective mitigation strategies and ensure power system resilience.

A. Reflections from the state-of-the-art

The reduction of inertia due to the emergence of PEI generation presents significant challenges for the energy transition [5]. This change in power system topology alters traditional stability classifications, as demonstrated by IEEE's revision of stability structures, with continuing investigations into stability margins [1].

For instance, adjustments to the Rate of Change of Frequency (ROCOF) standard have been necessary. Previously typically set below 1 Hz/s, some countries, like Denmark, now require standards as high as 2.5 Hz/s due to the influx of PEI generation [6], [7]. This indicates that future systems must respond to faster frequency deviations at higher PEI penetration levels, which can significantly impact protection systems and safe operations [8].

While lower inertia conditions are generally viewed negatively, the fast-acting mechanisms of PEI generation resources may offer promising solutions to the challenges they introduce. Studies suggest that maintaining large rotational inertia may not be optimal [9], and the Australian Energy Market Operator (AEMO) indicates that the rapid response of PEI generation could reduce the need for rotational inertia [5]. Understanding the impact of PEI generation on inertia levels will be crucial for maintaining system resilience during the energy transition, with Grid-Forming (GFM) converters potentially playing a vital role.

To expand knowledge on decreased inertia levels in interconnected power systems, utilizing large-scale models that facilitate interactions between various resources and load conditions is essential. This approach will enhance analyses of frequency and oscillatory stability concerning low inertia scenarios and the impact of PEI generation at higher inertia levels. A comprehensive understanding of the changing inertia landscape is vital for ensuring stability during the energy transition.

This paper highlights the intricacies of these challenges, offering insights into future inertia projections and the effectiveness of various mitigation strategies. By employing an advanced large-scale synthetic model, the study conducts intricate simulations to examine the energy transition's impact on power system stability using projected future scenarios.

The paper is structured into five sections: modeling, methodology, results, discussion, and conclusion with future work.

II. Modeling

The modeling approach in this study constructs a synthetic, large-scale representation of the Dutch Extra High Voltage (EHV) network projected towards 2050, as seen in Fig.1. Developed using publicly available information, this model reflects a high degree of electrification, incorporating substantial capacities of onshore and offshore wind and solar PV, along with a peak load scenario [10], [11]. The inertia values are derived from ENTSO-E's 2040 projections, encompassing a wide range of inertia constants and kinetic energy levels that reflect the uncertainties inherent in future power systems.

These projections account for various energy policy scenarios, indicating that inertia will vary by time of year, month, and day, as well as in response to different policy decisions. To capture this variability while minimizing simulation runs, inertia values are selected for the highest, lowest, and midpoint scenarios.

In the synthetic model, inertia is represented through the dynamic properties of synchronous machines at the interconnections, using the following conversion from inertia values to apparent power (MVA):

$$S\ [\text{MVA}] = \frac{E_{\text{kin}}[\text{MVAs}]}{H[\text{s}]} \tag{1}$$

This equation translates kinetic energy (E_{kin}) into the system's rated power (S) for a given inertia constant (H).

The case study assumes that PEI generation units operate with 50 % GFM converter technology using the Virtual Synchronous Machine (VSM) topology. The selection of GFM penetration levels and the controller type, based on a generic template from PowerFactory, was determined as part of a broader project and serves as a baseline for future GFM integration. The dispatch of solar PV (PV), offshore (WOZ), and onshore (WOL) wind, along with demand, is established on a percentage basis, with conventional generation units (e.g., nuclear) set at fixed levels, as detailed in Tab. I. These values reflect a predominantly PEI-reliant system, designed for a high offshore wind production scenario.

Flexibility resources, such as battery energy storage, fuel cells, electrolyzers, and interconnections, are managed by a Python script that balances generation and load based on residual supply-demand. For simplicity, these resources are equally distributed across the system. Power exchanges through interconnections are set to zero to establish a baseline, focusing on the internal dynamics of the Dutch power system. While future systems may rely on exchanges to manage a large influx of renewable generation, this study assumes a self-sufficient Dutch system to emphasize domestic integration impacts.

The interconnections' active and reactive power limits are based on the projected transmission capacity for 2050. HVDC interconnections are modeled using VSC MMC templates in PowerFactory, enhancing model accuracy despite not being central to the stability analysis.

This modeling approach establishes a robust foundation for analyzing stability and dynamics in future high-PEI scenarios, leveraging a large-scale synthetic model grounded in real-world projections.

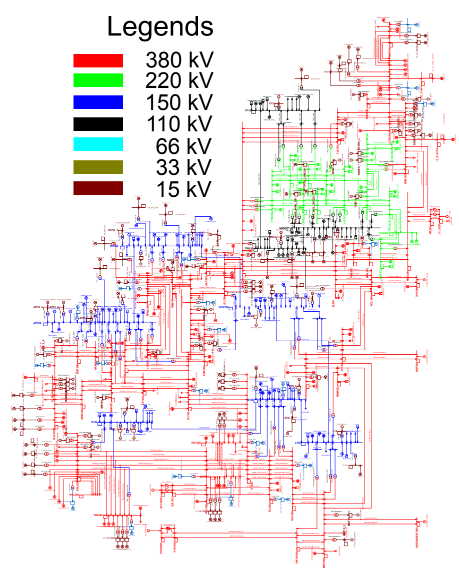

Fig. 1. Overview of the complete Synthetic model highlighting different voltage levels [12].

III. Methodology

The methodology adopted in this study is designed to simulate and analyze the combined impact of inertia constants and kinetic energy levels on the stability of a synthetic Dutch power system model projected for 2050. A flowchart depicting the methodology can be seen in Fig.2. The approach follows a sequential workflow with predefined simulation and processing structure. This allows for a streamlined process, easy to replicate and compare results, facilitating a streamlined

TABLE I. Distribution of generation, demand set points, and corresponding percentages based on peak supply

WOZ (GW / %)	WOL (GW / %)	PV (GW / %)	Flexibility (GW)	Conv. (GW)	Demand (GW / %)
47272.5 (90%)	2068.5 (10%)	8649.5 (5%)	12020	2000	47979.9 (100%)

process that is easy to replicate and compare results. Detailed descriptions of each step are provided below.

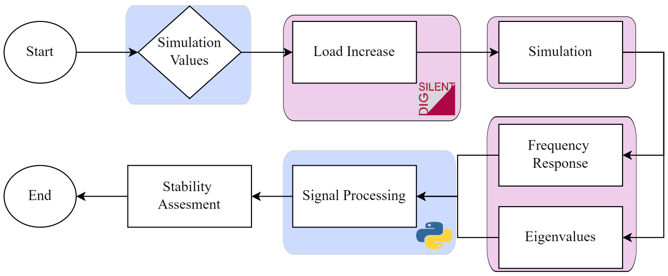

Fig. 2. Flowchart highlighting the simulation and assessment process.

The simulation values for inertia constants and kinetic energy levels are shown in Table II, covering the projected ranges from maximum to minimum. Kinetic energy levels are converted to apparent power using (1) to implement in the model. Each inertia constant is simulated across all kinetic energy levels, and vice versa, to capture all variations, as indicated by the ”fixed” parameter designation in the table.

TABLE II. Simulation Values for Inertia Constant and Apparent Power

Simulation	Levels	Fixed Parameter
Inertia Constant [s]	4.1, 2.25, 0.5	Apparent Power
Apparent Power [MVA]	439,025, 250,000, 60,976	Inertia Constant

The synthetic model simulates an extreme 5.6 GW load increase, representing over 10 % of the system's total load, distributed proportionally across Dutch load centers.

The simulations were conducted using PowerFactory RMS simulation, utilizing the built-in frequency and eigenvalue analysis tools. A Python script interfaced with PowerFactory was utilized to update the simulation parameters, ensuring a consistent approach to parameter adjustments. Automating these processes using Python enhances the structure of the analysis and simplifies the validation of results. Python was also used for signal prosessing and calculating the stability criteria.

Stability performance was assessed using two frequency metrics (ROCOF (2) and maximum deviation (3) and one angular stability metric (damping ratio ζ (4). ROCOF measures the frequency's rate of change, maximum deviation indicates the largest disturbance response, and ζ captures mode damping and oscillation frequency. ROCOF and maximum deviation values are compared based on relative changes, while damping ratios below 3 % are considered critical and those above 5 % sufficiently damped, as per literature [13], [14].

The frequency analysis focused on ROCOF and maximum deviation, while eigenvalue analysis was used to identify damping ratios and mode frequencies.

$$\text{ROCOF} = \frac{\Delta f}{\Delta t} \tag{2}$$

$$Max\ Deviation = \Delta f_{max} \tag{3}$$

$$\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{4}$$

This methodology enables a comprehensive investigation of the interplay between inertia constants, kinetic energy levels, and stability phenomena, providing valuable insights into the stability of large-scale interconnected systems. Although the study focuses on the Dutch power system, its synchronous connections to the broader continental European grid illustrate how variations in inertia and kinetic energy levels can impact overall stability across the region.

IV. Inertia Constant Analysis

A. Discussion

The investigation into the implications of projected inertia constants on future power system stability underscores a balance of potential advantages and challenges critical for strategic planning. Results presented in subsection IV-B indicate that systems with higher projected inertia constants exhibit enhanced stability, characterized by superior damping and reduced frequency deviations following disturbances. This suggests that higher inertia constants could play a vital role in maintaining system robustness under stress.

While higher inertia constants are associated with a slower frequency response, the trade-off analysis reveals overall gains in system stability due to improved damping, evidenced by reduced oscillations and lower frequency deviations during the settling phase. Consequently, systems with higher inertia constants may respond more resiliently to significant disturbances, albeit with less effective primary frequency restoration.

Conversely, lower inertia constants correspond to a more dynamic response, with rapid and pronounced oscillations. Although these systems can recover frequency swiftly, their heightened susceptibility to sustained oscillations presents potential challenges to stability. At the lowest kinetic energy levels, the risk of persistent oscillations extending beyond typical operational timeframes becomes more pronounced, highlighting the need for careful consideration in future system designs.

The analysis of frequency response variables, detailed in Table III, reveals critical behavioral changes across different projected inertia constants. For instance, the maximum ROCOF increases significantly with lower inertia constants, posing implications for the design and operation of protection systems sensitive to high ROCOF values. In severe cases, a threefold increase in ROCOF was observed, underscoring the scale of potential shifts in system behavior and the challenges they may pose.

The damping analysis presented in Figure 6 further highlights the critical role of inertia constants in ensuring future system stability. The system's modal behavior is predominantly characterized by inter-area modes, shaped by interconnections, typically observed within frequency ranges specified in [15]. The analysis also considered modes associated with grid-following controllers at a frequency of 0.63 Hz, which remain unaffected by inertia adjustments. Notably, variations in inertia constants reveal changes in modal characteristics, including shifts in frequencies for certain modes that continue to exhibit participation by the interconnections. This suggests that under specific operational conditions, these modes may alter their characteristics, making them less easily identifiable using traditional frequency ranges. Such findings indicate a potential evolution in the understanding and analysis of these modes, necessitating a rethinking of analytical approaches.

Overall, the results demonstrate that higher inertia constants contribute to increased damping ratios in inter-area modes, enhancing system stability. In contrast, the lowest inertia constant levels exhibit multiple modes that fall significantly below the 3 % and 5 % stability margins, with one mode showing a negative damping ratio, indicating growing oscillations. These findings underscore the risk of instability under certain inertia constant conditions, which could threaten the reliable operation of the Dutch power system.

B. Results

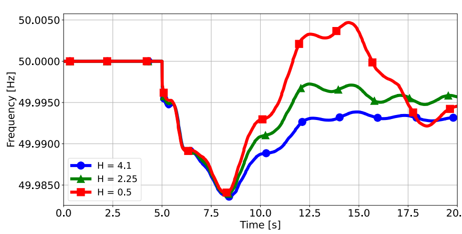

Fig. 3. Frequency response for a kinetic energy of 1800 GVAs.

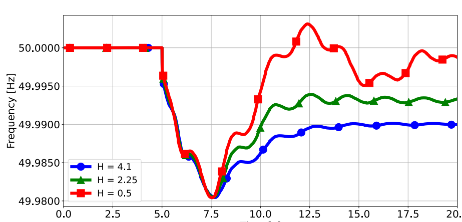

Fig. 4. Frequency response for a kinetic energy of 1025 GVAs.

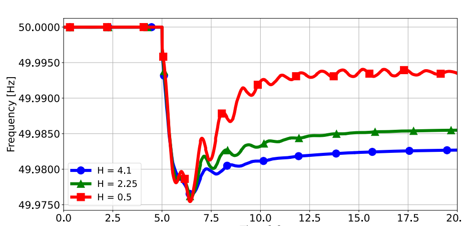

Fig. 5. Frequency response for a kinetic energy of 250 GVAs.

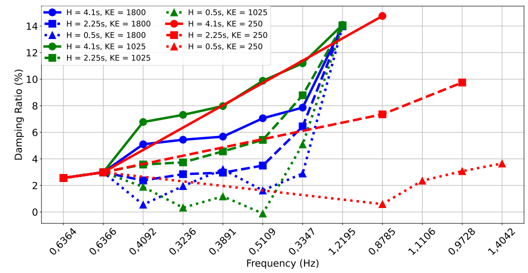

Fig. 6. Damping comparison across inertia constant levels.

TABLE III. Simulation parameters for inertia constant and kinetic energy analysis.

KE = 1800				
Case Index	**Frequency Nadir (Hz)**	**ROCOF (mHz/s)**		**Maximum Deviation (mHz)**
		100 ms	**500 ms**	
H = 4.1	49.9836	6.6	4.9	16.4
H = 2.25	49.9839	8.3	6.4	16.1
H = 0.5	49.9841	9.7	8.1	15.9
KE = 1025				
Case Index	**Frequency Nadir (Hz)**	**ROCOF (mHz/s)**		**Maximum Deviation (mHz)**
		100 ms	**500 ms**	
H = 4.1	49.9804	6.1	5.4	19.6
H = 2.25	49.9805	8.2	7.5	19.5
H = 0.5	49.9804	13.3	10.7	19.6
KE = 250				
Case Index	**Frequency Nadir (Hz)**	**ROCOF (mHz/s)**		**Maximum Deviation (mHz)**
		100 ms	**500 ms**	
H = 4.1	49.9764	7.5	6.2	23.6
H = 2.25	49.9760	14.1	10.6	24.0
H = 0.5	49.9754	23.1	17.3	24.6

V. Kinetic Energy Analysis

A. Discussion

The kinetic energy analysis, presented in section V and Table II, evaluates the system's frequency response and damping performance across varying kinetic energy levels for different inertia constants. The results indicate that higher kinetic energy levels lead to smaller maximum frequency deviations, suggesting an initial advantage in system stability. However, these levels are also associated with increased oscillations and longer settling times, highlighting a trade-off between stability and response speed.

Conversely, lower kinetic energy levels enable quicker settling but result in a lower steady-state frequency post-disturbance, demonstrating an inverse relationship with inertia constants. ROCOF values further illustrate this trade-off, with higher kinetic energy levels exhibiting lower ROCOF values. Although the disparity in ROCOF across kinetic energy levels is significant, it is less pronounced than in the inertia constant analysis, with the worst-case scenario showing a 2.5-fold difference. Notably, under the highest inertia constant scenarios, ROCOF values remain nearly identical across all kinetic energy levels, reinforcing the dominant influence of inertia constants on frequency dynamics.

The frequency analysis suggests that while lower kinetic energy levels offer advantages such as faster adjustments, they also introduce challenges, including rapid fluctuations or simultaneous occurence of several stability phenomena that could jointly and seriously threaten overall system stability.

The damping analysis presented in Figure 10 reveals that higher kinetic energy levels generally enhance stability margins by increasing damping ratios for inter-area modes. However, modes associated with the lowest kinetic energy levels are often absent in the plots, indicating a significant shift in system behavior, similar to the findings in the inertia constant analysis. Newly emerging modes typically exhibit higher frequencies compared to traditional low-frequency inter-area modes and demonstrate improved damping ratios. Aside from the unchanged grid-following modes, no additional modes with damping ratios below 10 % are observed.

The substantial reduction in kinetic energy alters the system's oscillatory behavior, presenting both potential benefits and challenges. A key advantage is that slow-acting inter-area modes, which are traditionally difficult to dampen, are transformed, allowing the rapid response of PEI generation-heavy systems to balance frequency deviations more efficiently within shorter timeframes. This synergy between fast oscillatory responses and rapid control actions could be a promising avenue for enhancing future power system stability.

However, the analysis also highlights major stability concerns at the lowest inertia constant levels, with certain scenarios leading to direct instability. While both the lowest and highest kinetic energy levels maintain stable responses, the system exhibits underdamped behavior, posing a risk of severe oscillations. This underscores the strong dependency on inertia constants and the necessity for explicit discussions on future projections to guide policymaking. Certain combinations of kinetic energy levels and inertia constants could lead to direct instability in future power systems, emphasizing the urgent need for countermeasures and strategic planning.

While the study primarily highlights significant stability concerns associated with projected inertia values, it also reveals potential improvements in stability due to shifts in system dynamic. This is particularly evident in systems operating at the lower end of the inertia spectrum—both in terms of inertia constant and kinetic energy—where the power system exhibits a faster response, contrasting with the traditionally slower dynamics of large-scale power systems. This transition presents opportunities for emerging technologies that leverage the rapid response capabilities of PEI controllers, enhancing system stability amid evolving conditions. The findings highlight the promise of advanced control strategies, such as GFM controllers, to optimize the integration of PEI-connected resources and support a stable power system.

Establishing a specific minimum kinetic energy level for safe power system operation is challenging due to the intrinsic relationship between inertia levels, system configuration, and varying load conditions. Reference [16] suggests a minimum inertia constant level of 2 seconds to ensure sufficient inertia for both short-term and long-term resilience in the future European power system. This is expected to be adjusted based on multiple factors in the future.

The numerical simulations provided in this study illustrate that reduced inertia constant levels of 2.25 seconds could lead to significantly degraded damping performance and tight stability margins when seen as a supplementary metric with varying kinetic energy levels. This indicates that defining minimum or maximum levels for inertia and kinetic energy may not fully capture the complexities of time-varying intrinsic stability issues, which depend on several factors such as the roll-out of GFM technology and the speed proliferation of novel technologies due to the desired acceleration of the energy transition.

Overall, the study indicates that certain inertia characteristics projected by ENTSO-E could significantly and adversely lower the dynamic stability of the Dutch power system in hypothetical futuristic conditions by 2040. Moreover, the presented software-based simulations point out the potential of occurrence of widespread propagation of instability phenomena across synchronously connected countries. This emphasizes the need for broader stability studies, including the application of higher modeling depth and advanced stability assessment methods. This is essential to define confident monitoring applications and effective control actions to ensure a secure and resilient power system throughout the energy transition.

B. Results

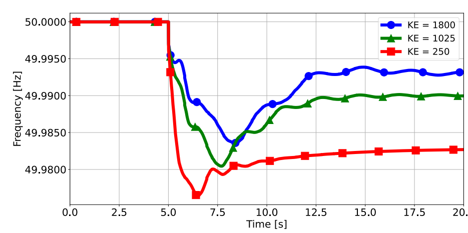

Fig. 7. Frequency response for an inertia constant of 4.1 s.

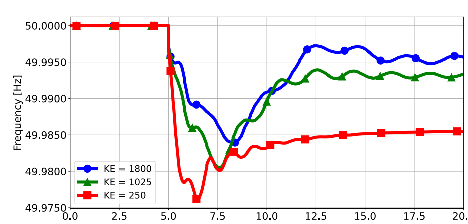

Fig. 8. Frequency response for an inertia constant of 2.25 s.

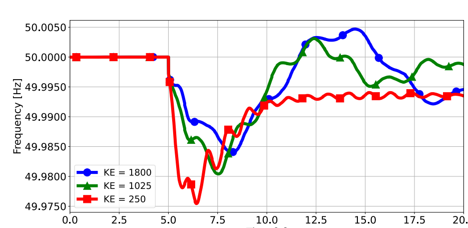

Fig. 9. Frequency response for an inertia constant of 0.5 s .

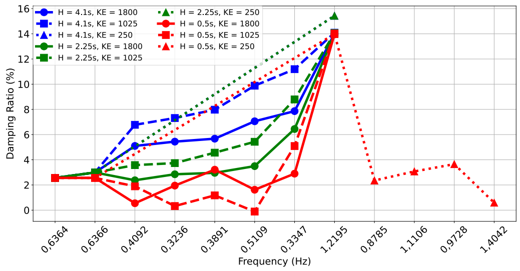

Fig. 10. Damping comparison across kinetic energy levels

VI. Conclusion

This study, based on ENTSO-E's future inertia projections and state-of-the-art stability assessment tools, provides a high-impact analysis of the effects of extreme disturbances on a hypothetical futuristic situation of the Dutch power system. Evaluations conducted on a synthetic model emphasize the crucial role of inertia in maintaining stability under large active power imbalances. The vulnerability of stability is especially critical under high penetration levels of components and subsystems coupled through power electronic converters. Relative high degree of fast active power - frequency support can effectively limit abrupt and fast frequency deviations and oscillations, whereas low degree or the absence of such capabilities entail high risk of instability. Numerical simulations also illustrate how reduced inertia also shifts the overall systemic dynamic performance toward a faster system response, creating challenges for advanced control strategies to properly manage adverse multi-converter dynamics.

Lower kinetic energy levels further transform the systemic dynamic performance, reinforcing the potential of fast-acting control systems. This highlights the emergence and possible predominance of time-varying stability phenomena and their coupling. Under these conditions, adaptive multi-objective control strategies, including improved forms of Grid-Forming control or new control concepts should be thoroughly investigated in future studies.

Overall, the study identifies significant risks in projected inertia values but also highlights opportunities for improved stability if appropriate control measures are implemented. Certain inertia combinations resulted in insufficient damping, with some scenarios exhibiting growing oscillations, making the system highly vulnerable to disturbances. Therefore, strategic planning and timely corrective actions are essential to ensure the reliable operation of the Dutch power system amidst the evolving energy landscape.

Future research should also focus on conducting advanced sensitivity analyses of inertia projections and exploring the implications of various energy policy scenarios to further inform system design and operational strategies. Supplementary studies based on higher modeling depth and hardware-in-the-loop-based evaluations are also essential to crosscheck the trustworthiness of existing stability study tools and controller design tools.

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