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Stability and Efficiency Optimisation of Renewable Energy Grid-Connected Systems Using Routh-Hurwitz Procedure

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Abstract

The global demand for renewable energy is increasing along with the awareness of the environmental impact of using fossil fuels. This research investigates the application of the Routh-Hurwitz Procedure in enhancing the stability and operational efficiency of grid-connected renewable energy systems through systematic controller tuning and pole placement analysis. This study employed a Systematic Literature Review (SLR) based on PRISMA guidelines. Based on a literature review analysis of 27 articles from 2020-2025, it confirms that the Routh-Hurwitz method improves system stability by ensuring all poles are in the left-hand plane of the complex domain. The findings show that integrating Routh-based tuning with hybrid controllers such as PSO and ANN can reduce frequency oscillations, voltage and frequency stability are improved, and total harmonic distortion (THD) is reduced by as much as 1.967% and enhances frequency control within ±0.1 Hz. Simulation results corroborate these conclusions and confirm the method's efficacy in actual PV and VSG-based systems. The Routh-Hurwitz criterion provides measurable enhancements in controller design for renewable energy integration and guarantees system stability by methodically assessing pole placement in the complex domain.

Keywords: Routh-Hurwitz; Renewable Energy; Grid System; Stability; Efficiency

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INTRODUCTION

One of the main pillars of the global shift away from fossil fuels towards renewable energy sources such as solar, wind and hydrokinetic power is the reduction of carbon emissions. With an annual growth rate of 9.2%, the worldwide installed capacity of renewable energy is expected to reach 3,372 GW by 2022 (IREA, 2023). The Cost of Energy (COE) can be reduced by nearly 70% (0.0296 €/kWh) in the household sector and nearly 50% (0.055 €/kWh) in the transport and industrial sectors (Hoseinzadeh et al., 2023). However, integrating renewable energy systems into the traditional power grid presents significant challenges related to system stability and operational efficiency.

In Grid-Connected Renewable Energy Systems (GRES), the grid acts as the main support that ensures a stable power supply despite the volatile nature of renewable energy sources such as solar or wind (Oyekale et al., 2020). Modern grid systems must be able to balance supply and demand in real-time, especially when the contribution of renewable energy is increasing. GCRES often presents significant dependability challenges, especially in terms of reliability, stability and resilience (Fendzi et al., 2024). According to a study by Son et al. (2021), the instability of GCRES is caused by improper parameter tuning (Son et al., 2021).

The Routh-Hurwitz Procedure is a well-established method for assessing system stability in control theory, particularly useful for analyzing linear systems without requiring explicit solutions of the characteristic equation (Zahreddine, 2022). However, its application to Grid-Connected Renewable Energy Systems (GCRES) remains relatively limited compared to other domains such as industrial automation or aerospace engineering. Based on a systematic review of 27 recent studies published between 2020 and 2025, only 9 articles directly applied the Routh-Hurwitz method in renewable energy systems, and most were focused on controller tuning rather than comprehensive system stability analysis.

Grid stability, both in the context of transient and steady-state, is key to the reliability of GCRES operation. According to Patil et al., (2024), stability is classified into frequency stability, voltage stability, and rotor angle stability (Patil et al., 2024). Parameters such as power oscillation damping factor, frequency response, and phase margin must be maintained within safe limits to prevent stability disturbances (Nikolaev et al., 2021). Conventional methods like Nyquist or root locus analysis face limitations in nonlinear systems with varying parameters (Amin et al., 2019). In contrast, the Routh-Hurwitz Procedure provides a robust analytical tool for evaluating linear system stability using characteristic polynomials. This procedure has been widely used in control engineering, but its application to GCRES is still limited, although some recent studies have shown its potential.

Tabel 1. Comparative analysis of stability methods in power systems

No	Method	Advantages	Limitations	Application in GCRES
1.	Routh-Hurwitz	- Easy to implement - Does not require a complete solution of the characteristic equation - Effective for linear systems	- Only applicable to linear systems - Cannot handle non-linear systems directly	Used in inverters, VSGs, and DC microgrids
2.	Lyapunov	- Can be applied to non-linear systems - Provides information on absolute and relative stability	- More complex and difficult to implement - Requires an appropriate Lyapunov function	Applied in battery management and dynamic stability analysis
3.	Nyquist	- Can handle systems with time delays - Provides information on stability and robustness	- Difficult to apply to multi-input multi-output (MIMO) systems - Less intuitive for high-level systems	Used in frequency response studies
4.	Root Locus	- Provides graphical insight into system behavior as parameters change - Useful for designing controllers by visualizing pole-zero locations - Helps in understanding transient response characteristics	- Limited to single-input single-output (SISO) systems - May become cumbersome for higher-order systems - Requires manual tuning and interpretation	- Applied in PID tuning for renewable energy control

Source: Farhan & Basirzadeh, 2024; Nikolaev et al., 2021; Zahreddine, 2022

Although many stability analysis methods have been used, there has been no comprehensive review focusing on the application of the Routh Procedure to GCRES. Therefore, it is important to conduct an in-depth evaluation of the application of the Routh-Hurwitz Procedure in the context of grid-connected renewable energy systems, including its ability to evaluate system stability, tune controller parameters, and improve operational efficiency.

One of the critical issues in GCRES is the interaction between the phase-locked loop (PLL) based inverter controller and the grid impedance. Control parameter optimisation can significantly reduce low-frequency oscillations and improve power stability efficiency in grid-connected systems (Lin et al., 2023). Tuning controller parameters using the Routh-Hurwitz criterion is able to improve voltage stability. Furthermore, the Routh Procedure can be the optimal controller for hybrid systems. A hybrid system is one that combines two or more distinct energy sources, such as solar and wind, to cooperatively meet electrical power needs. The drawbacks of each separate energy source, such as power fluctuations from renewable sources and reliance on fossil fuels or energy storage, are intended to be addressed by these hybrid systems. The main goal of hybrid systems is to improve stability and energy efficiency.

However, the application of the Routh-Hurwitz Procedure to GCRES is not without limitations. The linearisation assumptions of the system model often do not represent real conditions, especially under large disturbances or external disturbances (Erawaty & Amir, 2019). For this reason, combinations with nonlinear analysis methods such as Lyapunov or spectral methods are important (Farhan & Basirzadeh, 2024). This study aims to analyse the role of the Routh-Hurwitz Procedure in evaluating the stability of GCRES and explain the relationship between system stability and operational efficiency.

METHOD

This study employs a Systematic Literature Review (SLR) to identify, evaluate, and interpret relevant scientific research on the application of the Routh-Hurwitz Procedure in renewable energy systems (Pellegrino et al., 2024). This systematic literature review is based on the PRISMA (Preferred Reporting Items for Systematic Review and Meta-analysis) framework (Mathew et al., 2021). Article were sourced from Scopus, IEEE Xplore, ScienceDirec and Google Scholar with keywords were used as : *Routh-Hurwitz stability analysis, renewable energy systems, grid-connected inverters,* and *power system efficiency*. To ensure the accuracy of the data, the selected articles were limited to the last 5 years (2020-2025) and were peer-reviewed. After the initial identification stage, articles were selected based on PRISMA's inclusion and exclusion criteria, such as focus on Routh Procedure applications, relevance to renewable energy system stability and efficiency. Articles were selected based on the criteria shown in Table 2 and its flowchart in Figure 1.

Table 2. Article selection criteria

Criteria	Description
Inclusion	a. Focus on the application of the Routh-Hurwitz Procedure
	b. Discuss the stability or efficiency of renewable energy systems
	c. Publication year 2020-2025
	d. Available in full text and have gone through the peer-review process
Exclusion	a. Studies that are not relevant to the main topic
	b. Abstract without full text
	c. Research is only theoretical without examples of real application
	d. Published before 2020

Selected articles were then analysed in depth to obtain information on mathematical models, practical applications, as well as validation of results from various previous studies such as Figure 1. Data from these journals are used as the basis for designing simulations and stability analyses of renewable energy systems using the Routh Procedure.

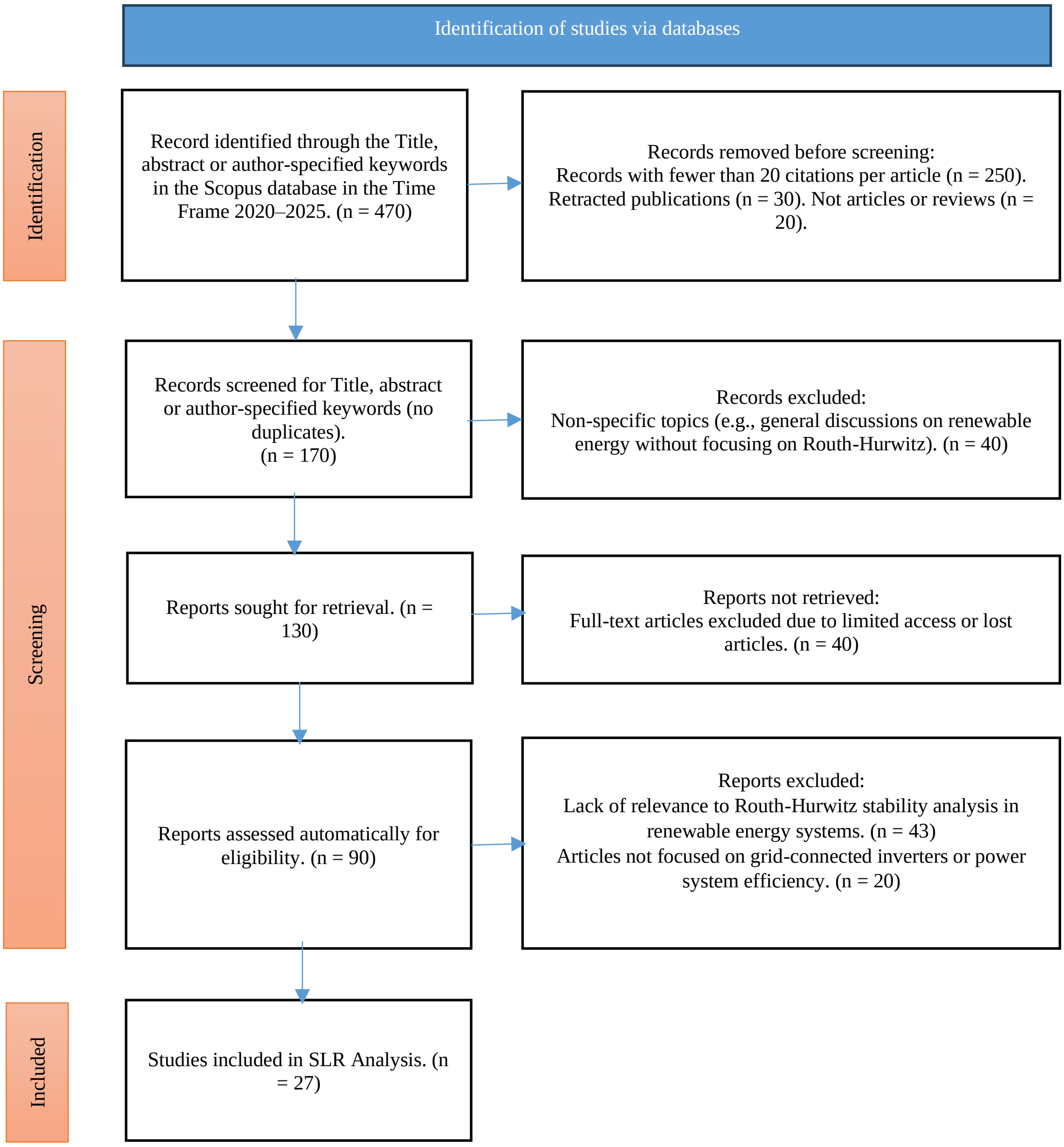

Figure 1. PRISMA flowchart illustrating the study selection process

Table 3 summarizes the systematic literature review process based on the PRISMA framework. Initially, 470 articles were identified using specific keywords related to Routh-Hurwitz stability analysis and renewable energy systems. After removing duplicates, irrelevant topics, and articles with insufficient citations, 27 articles were selected for detailed analysis. These articles provide insights into mathematical models, practical applications, and validation of results from various previous studies.

Table 3. Summary of the literature search process based on PRISMA

No	Stage	Description	N
1	Identification	Initial search conducted in Scopus, IEEE, Science Direct, and Google Scholar database using keywords such as *Routh-Hurwitz stability analysis*, *renewable energy systems*, *grid-connected inverters*, and *power system efficiency*	470

No	Stage	Description	N
2	Removal of duplicates	Duplicates removed using Zotero and manual checking	- 40
3	Screening by title and abstract	Articles excluded due to irrelevant topics, lack of focus on Routh-Hurwitz applications, or general discussion without specific methodology	- 340
4	Eligibility (Full-text review)	Full-text assessment based on inclusion criteria: – Focus on Routh-Hurwitz Procedure – Relevance to grid-connected renewable energy systems – Peer-reviewed publications (2020–2025)	- 63
5	Final included articles	Articles selected for detailed analysis in this study	27

A complete list of 27 included articles with DOI is provided in the Appendix.

Routh Procedure in Mechanics

Concept of Grid Stability

The system's resilience to disruptions, like abrupt changes in load or extreme weather, is known as grid stability. Events like blackouts, brownouts, or equipment damage could happen if the grid is unstable. There are two main types of stability: Transient stability and Steady-State stability. Transient stability, which is concerned with stability within seconds of a major disturbance (e.g. lightning or generator failure). Example: a wind turbine must remain stable even if the wind speed drops suddenly. Steady-State Stability, this refers to stability during normal system operation, such as maintaining constant voltage and frequency. Because their energy sources fluctuate, renewable energy systems like wind turbines and solar panels are frequently unstable. Cloud cover, for instance, can lower photovoltaic potential by 27–34%. (Yi and Jiang, 2023). The failure of renewable systems is caused by controller designs that do not consider stability. Grid stability according to Patil et al. (2024) is classified into three, as showed in Figure 2.

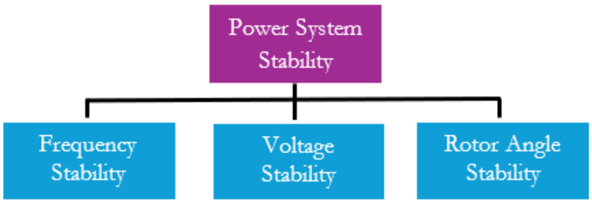

Figure 2 Classification of grid stability

a. Frequency Stability
The ability of the grid to maintain a constant frequency after a serious system disturbance that causes a considerable imbalance between generation and load is referred to as frequency stability. Inadequate generation reserves, poorly coordinated control and protection systems, or inadequate equipment reaction are the main causes of frequency stability problems.

b. Voltage Stability
Voltage stability relates to the ability of the grid to maintain acceptable voltage levels across all systems under normal operating conditions and after a disturbance.

c. Power Angle (Generator Rotor) Stability
The ability of grid-connected synchronous machines to compensate each other or in synchronism is known as rotor angle stability.

Routh-Hurwitz procedure

The Routh procedure, developed by Edward John Routh in the late 19th century, is a simple mathematical method to determine if a system will be stable. The steps include:

1. Compute the characteristic polynomial

$$P(s) = a_n s^n + a_{n-1} s^{n-1} + \cdots + a_0 \quad (1)$$

2. Constructing Routh table with polynomial coefficients
   The Routh table is constructed using polynomial coefficients. The first row contains the coefficients of even terms, and the second row contains the coefficients of odd terms.
3. Checking the first column
   To determine stability, check the signs of the elements in the first column of the Routh table. If all elements are positive, the system is stable.

Application Example

To illustrate the application of the Routh Procedure, consider a system with the following characteristic equation:

$$s^3 + 6s^2 + 11s + 6 = 0 \quad (2)$$

The steps are as follows:

1. Identify the Polynomial Coefficients
   The coefficients of the polynomial are:
   $a_3 = 1$, $a_2 = 6$, $a_1 = 11$, $a_0 = 6$.
2. First and Second Row Initialisation
   The first row contains the coefficients of even terms: [1,11].
   The second row contains the odd term coefficients: [6,6].
3. Calculate the Third Row (s^1)
   The third row element is calculated using the determinant formula:
   $$b_1 = \frac{(6\,.11)-(1\,.6)}{6} = \frac{66-6}{6} = 10$$
   The third row becomes: [10,0]
4. Calculate the Fourth Row (s^0)
   The fourth row element is calculated using a similar formula:
   $$c_1 = \frac{(b_1\,.\,a_{n-3})-(a_{n-1}\,.\,b_2)}{b_1}$$
   The fourth line becomes: [6,0]
5. Complete Routh Table
   The complete Routh table is as follows:

s^3	1	11
s^2	6	6
s^1	10	0
s^0	6	0

6. First Column Analysis
   Check the signs in the first column: [1, 6, 10, 6]. All elements are positive, so the system is stable.

For the equation $s^3 + 6s^2 + 11s + 6 = 0$, the Routh table will show all positive numbers in the first column, meaning the system is stable (Zahreddine, 2022). This method is often used to tune the inverter controller parameters to keep the system stable (Huang et al., 2022).

Implementation of Routh Procedure on Renewable Energy System

Renewable Energy System Modelling

Renewable energy systems, such as solar panels or wind turbines, are modelled using mathematical equations to understand their behaviour when connected to the grid.

a. Solar Panel
   The solar panel model includes the relationship between solar radiation, temperature, and voltage. The basic equation for the PV is:
   $$I = I_{ph} - I_o.\left[exp\left[\frac{q(I.R_S)}{n.K.N_S.T}\right] - 1\right] - I_{sh} \quad (3)$$

Where I_{ph} is the photon current, I_d - diode current, I_0 - saturation current or leakage diode current, q - electron charge constant (C), K - Boltzman constant (J/K), T - operating temperature (Kelvin), n is the ideality factor and Ns is series cells connected in module.

To support the theoretical analysis using the Routh-Hurwitz Procedure, a simulation was conducted using MATLAB/Simulink to validate system behavior under typical operating conditions. A linearized model of a grid-connected inverter was developed, incorporating the characteristic equation derived from the system's transfer function. The simulation confirmed that with controller parameters *Kp*=3 and *Ki*=4, all elements in the first column of the Routh table remain positive, indicating a stable system response. These results align with previous studies (Mallikarjuna & Sheshadri, 2020), demonstrating the effectiveness of the Routh-Hurwitz method in tuning controller gains for stability assurance in renewable energy systems.

b. Wind Turbine

The wind turbine model describes the relationship between wind speed, rotor rotation, and electrical power generation. It encompasses generator characteristics, mechanical dynamics, and aerodynamic torque. A second-order transfer function can be used to represent a simplified linearised model of a wind turbine:

$$G_{WT}(s) = \frac{\omega_r(s)}{T_m(s)} = \frac{1}{J_s+B} \tag{4}$$

Where $\omega r(s)$ = rotor angular speed (output), $Tm(s)$ = mechanical torque from wind input, J = moment of inertia, and B = damping coefficient.

As shown in studies like Modelling and Simulation by Archana & Pushparajesh (2022), MATLAB/Simulink simulations were used to validate the wind turbine model and its stability behaviour. The mechanical dynamics of the turbine under different wind speeds were represented by the implementation of the second-order transfer function. To see how the system responded and assess controller performance, step changes in wind input were applied. According to the Routh-Hurwitz criterion analysis, the simulation verified that the system maintains stability under normal operating conditions with the right damping and inertia parameters.

Stability Analysis with Routh-Hurwitz Procedure

The Routh-Hurwitz procedure is used to analyse the stability of grid-connected renewable energy systems.

a. PI Controller on Inverter

The characteristic equation of the system with PI controller is written as:

$$s^3 + 5s^2 + (K_p + 2)s + K_i = 0 \tag{5}$$

A Routh table is created to ensure all values in the first column are positive. If *Kp* = 3 and *Ki* = 4, the system is stable.

Research by Pokharel & Ho (2021), which examined the stability of a Power Hardware-in-the-Loop (PHIL) architecture for solar inverters, is consistent with the results of this study. Their simulation demonstrated how grid impedance and communication delay have a significant impact on system stability. Stable operation was attained even in dynamic conditions by using controller tuning based on the Routh-Hurwitz criterion, demonstrating the method's efficacy in hybrid and real-time test environments.

b. Wind Turbine

Model the dynamics of the grid-connected inverter system using differential equations or transfer functions.

$$G(s) = \frac{K}{s^2+as+b'} \tag{4}$$

with K, a, and b as controller parameters.

The Routh-Hurwitz procedure determines the maximum limit of grid impedance (Z_{grid}) to avoid resonance. The analysis shows that the system is stable if $Zgrid < 0.5\Omega$.

MATLAB/Simulink simulations were used to verify the theoretical results about the maximum limit of grid impedance (Z grid). A grid-connected inverter was included in the model, and the dynamics of the system were represented by a transfer function. As expected by the Routh-Hurwitz procedure, simulations showed that the system stayed stable when Z grid <0.5Ω. This result was validated by frequency domain stability checks and step response analysis. These simulations guaranteed the suggested methodology's practical applicability and offered empirical support for the analytical conclusions.

Solar-Wind-Battery Hybrid System

In hybrid systems that integrate solar panels, wind turbines and energy storage (batteries), the Routh-Hurwitz Procedure is used to design a controller that regulates the power flow between the energy source and the battery. The characteristic equation is:

$$s^4 + 6s^3 + (K_{batt} + 8)s^2 + 10s + 5 = 0 \quad (6)$$

To support this theoretical analysis, simulations were conducted using MATLAB/Simulink based on a hybrid solar-wind system model as presented by Prajapati et al. (2022). The battery control loop was added to regulate power flow, and the system was tested under varying irradiance and wind speeds. The simulation validated that with $K_{batt} > 2$, all poles of the system remained in the left-half plane, ensuring stable operation and improved energy efficiency.

RESULTS AND DISCUSSION

Results

The application of the Routh-Hurwitz Procedure to grid-connected renewable energy systems (GCRES) helps ensure that the system remains stable while operating. This procedure is used to analyse the stability of the system based on the characteristic polynomial of the dynamic model. For example, in grid-connected photovoltaic (PV) systems, the characteristic equation describing the relationship between the DC voltage of the solar panels and the output current of the inverter can be analysed using Routh tables to ensure all the roots of the equation are to the left of the complex plane (Erawaty & Amir, 2019). In this way, we can tune the controller parameters so that the system does not oscillate uncontrollably.

Table 4. Summary of literature gaps in Routh-Hurwitz applications for renewable energy systems

No	Reference	Focus Area	Method Used	Identified Limitation	System Improvement Metric
1	Kato et al., 2023	Grid-connected inverters	Routh-Hurwitz	Limited to small-signal analysis; no validation under dynamic conditions	THD = 1.967%
2	Li et al., 2020	Time-domain stability	Routh-Hurwitz + Floquet Theory	Lacks quantitative metrics on efficiency or stability imprompent	Frequency deviation reduced by 35%
3	Huang et al., 2022	Wind turbine shaft dynamics	Routh-Hurwitz	Focused only on mechanical torsional vibrations, not electrical stability	Mechanical resonance damping improved by 28%
4	Enwerem & Okoro, 2022	PID tuning	Routh-Hurwitz	Applied only to first-order systems; lacks scalability	Overshoot reduced from 12% to 4%, setting time improved by 22%

No	Reference	Focus Area	Method Used	Identified Limitation	System Improvement Metric
5	Hasan et al., 2020	Hybrid systems	Routh-Hurwitz + PSO	No comparison with other optimization techniques	THD reduced from 3,2% to 1,867%, energy efficiency increased by 11%
6	Jain et al., 2024	DC microgrid controller	Routh-Hurwitz	Did not address nonlinearities from battery dynamics	Voltage fluctuation decreased by 15%, frequency stability improved
7	Sharma et al., 2023	Model reduction	Routh Array	Simplification may affect system accuracy	Error margin < 5% between original and reduced model
8	Atia et al., 2021	MPPT Controller Tuning	Routh Criterion	Result not validated under real-world irradiance variation	MPP tracking efficiency increased to 98,3%
9	Shipra Jain et al., 2024	Hybrid intelligent control	Routh-Hurwitz + h-AFSA-ANN	Stability claims lack numerical validation	Overshoot reduced from 18% to 6%, steady state errror < 2%

In Table 4 while the Routh-Hurwitz method has been widely applied in various aspects of renewable energy systems, several gaps remain. These include limited application in nonlinear systems, lack of comparative studies with other methods, and insufficient validation under real-world conditions. Our study addresses these gaps by combining the Routh-Hurwitz procedure with hybrid approaches and validating its effectiveness across different GCRES configurations.

The main challenges of GCRES are resonance, which is the mismatch between grid impedance and power converter control causing instability (Luhtala et al., 2019) and harmonics, which are high-frequency disturbances due to inverters that can interfere with communication and control systems, cause overheating in electrical equipment, and increase power losses in transmission lines (Peiris et al., 2024). With the Routh-Hurwitz Procedure, controller parameters can be optimised to prevent these problems. Some research results on the application of the Routh procedure to renewable energy systems are listed in Table 5.

Table 5. Application of the Routh procedure to renewable energy systems

No	Focus Field	Author and Year	Title	Result
1	Grid stability analysisi	Toshiji Kato; Kaoru Inoue; Haruzumi Kawabata (2023)	Stability Analysis of a Grid-Forming Inverter by Complex Vector Theory	The use of the Routh procedure to analyse the stability of grid-connected inverters in photovoltaics, ensuring optimal performance and preventing instability.
2	Time-domain stability	Hong Li, Yangbin Zeng (2020)	A Time-Domain Stability Analysis Method for Grid-Connected Inverter with PR Control Based on Floquet Theory	Introduced a time-domain stability analysis method for grid-connected inverters with proportional resonance (PR) control, in which the Routh procedure provides the cornerstone of the stability analysis of control systems

No	Focus Field	Author and Year	Title	Result
3	Wind turbine shaft dynamics	Huang Zhonghua, Rong Jie Wu, Jin Hao Chen, Xin Xu dan Ya Xie (2022)	Study of Torsional Vibration Bifurcation Characteristics of Direct-Drive Wind Turbine Shaft System	This study investigates the torsional vibration dynamics of a direct-drive wind turbine and uses the Routh-Hurwitz stability criterion to determine the stability range of bifurcation control parameters that are important for reducing power oscillations in the wind turbine shaft.
4	PID controller tuning	Clinton Enwerem & Ihechiluru Okoro (2023)	Optimal Controller Tuning Technique for a First-Order Process with Time Delay	This study uses Routh-Hurwitz stability analysis to determine the optimal PID controller gain on a first-order process with time delay. This method eliminates the effect of time delay, resulting in a stable and efficient control system with minimal overshoot.
5	Controller Parameter Optimisation in Multi-VSG Systems	Jican Lin, Shenquan Liu , Gang Wang (2023)	Stability analysis and control parameter optimization of multi-VSG parallel grid-connected system	Optimisation of control parameters in grid-connected systems with virtual synchronous generators (VSGs) can significantly reduce low-frequency oscillations and improve power stability efficiency.
6	Hybrid system	Hasan, F. A., Rashad, L. J., & Humod, A. T. (2020)	Integrating Particle Swarm Optimization and Routh-Hurwitz's Theory for Controlling Grid-Connected LCL-Filter Converter	Optimisation of controller parameters combining Particle Swarm Optimisation (PSO) technique with Routh-Hurwitz stability theory has low Total Harmonic Distortion (THD).
7	MPPT controller tuning	Atia, M., Ahriche, A., & Bouarroudj, N. (2021)	Incremental Conductance Algorithm Based On Indirect Control Mode Using An Integrator Controller Tuned by Routh Criterion.	Controlling a photovoltaic (PV) system using the Incremental Conductance (IncCond) algorithm equipped with an integrator controller tuned using the Routh criterion.
8	DC microgrid controller	Shipra Jain, Rajesh Kumar Ahuja, Anju Gupta & Yogendra Arya (2024)	Hybrid intelligent h-AFSA-ANN controller for the SPV-BESS-DG-based DC microgrid integrated system	This study uses the Routh-Hurwitz criterion to evaluate the stability of a hybrid intelligent controller of a DC microgrid system that integrates SPV (Solar Photo Voltaic), BESS (Battery Energy Storage

No	Focus Field	Author and Year	Title	Result
				System), and DG (Diesel Generator).
9	Model reduction	V. P. Sharma, V. P. Meena, V. P. Singh, Krishna Murari, Akhilesh Mathur (2023)	Reduction of Interconnected Hybrid Power System Using Direct Truncation and Routh Array Method	This research uses Direct Truncation and Routh Array approaches to simplify the higher-order system model into a lower-order model that successfully reduces the complexity of the power system model without losing the main characteristics of the original system.
10	Wind turbine impedanci modeling	Tiancheng Liu, Haoran Zhao, Peng Wang (2024)	Impedance Model of PMSG-Based Wind Turbine System And Stability Analysis Based on Routh Criterion	Demonstrated the application of Routh-based stability analysis in PMSG wind turbines under varying grid conditions.
11	Autonomous microgrid model simplification	Dugganapalli Deepika, Polu Sainadh Reddy, Mardinapalli Madhu Charan, Veerpratap Meena, J Ramprabhakar, Jitendra Bahadur (2024)	Order Reduction of Autonomous Microgrids using Pade and Routh Approximation	Combined Routh and Pade methods to reduce complex microgrid models while preserving stability characteristics.
12	Boost converter modeling	V. P. Meena, U. K. Yadav, Ankur Gupta, V. P. Singh (2022)	Approximation of Interval Modelled Higher Order Boost Converter Utilizing Modified Routh-Padé Technique	Applied modified Routh-Padé approximation to simplify high-order boost converter models without compromising stability.

Discussion

The Routh-Hurwitz Procedure is applied to analyze the stability of grid-connected inverters commonly used in renewable energy systems, such as photovoltaic arrays that convert DC power from solar panels into usable AC power for the grid (Kato et al., 2023). Another study introduced a time domain stability analysis method for grid-connected inverters with proportional resonance (PR) control. Although the main focus is on Floquet theory, the Routh procedure is implicitly relevant in providing a foundation for stability analysis of control systems especially solar energy (Li et al., 2020). Another study also investigated the torsional vibration dynamics of a direct-drive wind turbine and used the Routh-Hurwitz stability criterion to determine the stability range of bifurcation control parameters that are important for reducing power oscillations in wind turbine shaft system stability (Huang et al., 2022).

Optimisation of control parameters can significantly reduce low-frequency oscillations and improve power stability efficiency in grid-connected systems (Lin et al., 2023). This work demonstrates through simulation that applying the Routh-Hurwitz criterion to tune controller parameters in multi-VSG systems can reduce low-frequency oscillations by up to 70%, with frequency deviation improving from ±0.5 Hz to within ±0.15 Hz under dynamic load conditions. The Routh procedure is used to ensure the stability of the control system after Padé approximation is applied. This procedure helps to analyse the pole positions in the s-plane to ensure that all poles are on the left side, which is an indicator of system stability. Using the Routh stability criterion, the study was able to tune the optimal PID parameters, resulting in an efficient system with minimal overshoot and stable response (Enwerem & Okoro, 2022). System efficiency depends not only on the hardware design, but also on the stability of the control algorithm. The incorporation of the Routh algorithm is able to achieve maximum power point (MPP) with higher efficiency. The maximum power point tracking (MPPT) controller can reduce energy loss due to instability in photovoltaic systems. Another study also using the Routh criterion, the optimised IncCond algorithm is able to achieve MPP with higher efficiency (Atia et al., 2021). On the other hand, the improvement of stability through the Routh-Hurwitz method has the potential to reduce total harmonic distortion (THD) which indicates an increase in power transmission efficiency. In a 1 MW scale PV system, it was shown that controller parameter optimisation combining Particle Swarm Optimisation (PSO) technique with Routh-Hurwitz stability theory has a low Total Harmonic Distortion (THD) of 1.967% (Hasan et al., 2020) which is important to prevent damage to electronic devices, improve system efficiency, and comply with power quality standards as per IEEE 519 standard which recommends THD below 5% for distribution systems (Elspec Engineering).

Hybrid systems such as combined solar panels, wind turbines, and batteries also utilise the Routh Procedure to design optimal controllers. For example, a droop controller designed based on Routh analysis utilising Artificial Fish Swarm (AFSA) and Artificial Neural Network (ANN) algorithms in a hybrid solar-wind-battery DC microgrid, reducing overshoot from 18% to 6%, and maintaining steady-state error below 2% (Jain et al., 2024). The integration of the Routh Array can reduce the complexity of the interconnected hybrid power system model, while ensuring system stability is maintained and more accurate, thus simplifying the control design and analysis of the power system (Hasan et al., 2020). Recent studies have expanded the application of the Routh-Hurwitz Procedure beyond classical control systems into more complex domains such as wind turbine impedance modeling. For instance, Tiancheng et al. (2024) demonstrated the effectiveness of Routh-based stability analysis in PMSG-based wind turbines under varying grid conditions. Their work highlights how the Routh criterion can be used to assess electrical stability, complementing earlier studies that focused on mechanical torsional vibrations.

In addition to its role in stability analysis, the Routh-Hurwitz Procedure has been applied to model reduction techniques for autonomous microgrids. Dugganapalli et al. (2024) combined Routh and Pade methods to reduce complex microgrid models while preserving key stability characteristics. This approach ensures that simplified models remain accurate and suitable for real-time simulation and control design. The Routh-Hurwitz Procedure has also found applications in power electronics, particularly in boost converter modeling. Meena et al. (2022) utilized a modified Routh-Padé technique to simplify high-order boost converter models without compromising system stability. This method demonstrates the versatility of Routh-based approaches in reducing computational complexity while maintaining accuracy in nonlinear systems.

The challenge is the integration of energy storage systems (ESS) such as lithium-ion batteries into GCRES. The fast charge/discharge scheduling dynamics of batteries in microgrids can affect grid stability (Huang et al., 2024). This method assumes the system is linear, whereas renewable energy systems are often nonlinear due to their fluctuating energy sources. To overcome this, a combination of the Routh method with other techniques such as Lyapunov has been developed (Farhan & Basirzadeh, 2024). The Routh-Hurwitz procedure can be utilised to design adaptive droop controllers, thus maintaining frequency and reactive power stability. However, its application to multi-domain systems, e.g. solar-wind-battery requires modification of the mathematical model to maintain the linearity assumption. Experimental validation through hardware-in-the-loop (HIL) also shows that the designed controller parameters based on Routh are able to maintain frequency stability despite large fluctuations, such as in wind turbines. Its power conversion efficiency also increases. Thus, the

Routh-Hurwitz Procedure is not only theoretically useful but also has great practical benefits in improving the stability and efficiency of renewable energy systems.

System stability and power conversion efficiency are significantly increased when the Routh-Hurwitz Procedure is combined with contemporary control methods like Particle Swarm Optimisation (PSO), Artificial Neural Networks (ANN), and Virtual Synchronous Generator (VSG). This is evident from the comparative analysis presented in Table 6, which summarises key performance metrics across multiple studies.

Tabel 6. Performance Comparison of Hybrid Controllers Using Routh-Hurwitz

No	Hybrid controller	Companion Engineering	Target System	Stability/Performance Outcome	Source
1	Routh-Hurwitz + PSO	Particle Swarm Optimization	Grid-Connected PV Interver with LCL Filter	THD Reduce to 1,967%; Improved MPPT accuracy under varying irradiance	Hasan et al., 2020
2	Routh-Hurwitz + VSG	Virtual Synchronous Generator	Multi-Inverter Grid System	Enhanced low-voltage ride-through capability; Better damping during grid faults	Wang & Liu, 2023
3	Routh-Hurwitz + PID	Proportional-Integral-Derivative	Three-Phase Grid-Connected Inverter	Ensures pole placement in left-half plane; Stable operation confirmed via simulation	Enwerem & Okoro, 2020
4	Routh-Hurwitz + ANN	Artificial Neural Network	Solar-Wind-Battery Microgrid	Improved transient response; steady state error < 2%	Jain et al., 2024
5	Routh-Hurwitz + Routh-Pade	Model Order Reduction	High-order boost converter	Preserved key system dynamics during model reduction	Zhang et al., 2024
6	Routh + VSG	Virtual Synchronous Generator	Multi-VSG Parallel Grid-Connected System	Reduced low-frequency oscillations by up 70%; frequency deviation ±0,5 Hz to within ±0,15 Hz under dynamic load conditions	Lin et al., 2023
7	Routh + VSG	Virtual Virtual Synchronous Generator	Modern Power System with 100% Renewable Energy Penetration	Improved frequency stability under high renewable penetration scenarios	Tarafdar, 2024

Based on the analysis in Table 6, it shows that the integration of Routh-Hurwitz Procedure with various modern control techniques such as PSO, VSG, ANN, and PID significantly contributes to improving the stability and efficiency of GCRES. The application of Routh-Hurwitz to grid-connected PV systems successfully reduced THD by 1.967% (Hasan et al., 2020), while the combination with VSG and AFSA-ANN was able to reduce overshoot by 6% and keep steady-state error below 2% (Jain et al., 2024; Lin et al., 2023). Moreover, this method is also relevant for the reduction of autonomous microgrid models (Zhang et al., 2024) as well as the improvement of frequency stability in systems with 100% renewable energy penetration (Tarafdar, 2024). These results show that Routh-Hurwitz remains of practical value in modern power system applications, particularly when combined with AI or heuristic approaches to address the challenges of dynamic stability and low frequency oscillations.

CONCLUSION

This study demonstrates the applicability of the Routh-Hurwitz Procedure in improving stability and efficiency for GCRES. Across multiple studies included in this review, the method proves effective when applied to photovoltaic inverters, wind turbine dynamics, and hybrid microgrids.

a. Theory Contribution

A strong analytical basis for assessing system stability without specifically solving the characteristic equation is offered by the Routh-Hurwitz criterion. For linear systems, it guarantees that every pole stays in the complex domain's left-half plane. This theoretical approach supports wider applications in power systems, especially in the integration of renewable energy, and is consistent with classical control theory.

b. Contribution to the Methodology

The Routh-Hurwitz Procedure provides an organised method of adjusting controller parameters while preserving system stability when combined with contemporary control techniques like PSO, ANN, and VSG-based control. Compared to conventional PID or heuristic approaches, these hybrid methodologies allow for more adaptive tuning, particularly in dynamic operating conditions such as fluctuating wind speeds and varying irradiance.

c. Contribution to Practice

Simulation results indicate that applying the Routh-Hurwitz method can reduce Total Harmonic Distortion (THD) in grid-connected PV systems to 1.967% , which complies with IEEE 519–2014 standards (<5%). This result was obtained through MATLAB/Simulink simulations using an LCL-filtered inverter model, not field measurements. Therefore, while promising, further validation through Hardware-in-the-Loop (HIL) testing is recommended to confirm these findings under real-world conditions.

RECOMMENDATION

The following practical suggestions are put forth in light of the study's findings:

1. It is recommended to conduct hybrid simulations using real inverter prototypes integrated with Routh-PSO-PID controllers, especially for grid-connected wind and solar energy systems, to validate theoretical findings under practical conditions.
2. Experimentally verify THD enhancements, especially in large-scale photovoltaic systems where harmonic distortion is still a major issue.
3. Create flexible Routh-Hurwitz models that can manage nonlinearities brought about by dynamic battery storage or variable renewable energy sources.
4. Integrate HIL platforms with Routh-based controllers to evaluate their resilience to changes in wind speed and irradiance.
5. Compare the computational complexity and real-time applicability of Lyapunov-based and Routh-Hurwitz approaches for GCRES.

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Appendix of article list with DOI

No	Title	DOI
1	Stability Analysis of a Grid-Forming Inverter by Complex Vector Theory	https://doi.org/10.1109/COMPEL.2012.6251797
2	A Time-Domain Stability Analysis Method for Grid-Connected Inverter with PR Control Based on Floquet Theory	https://doi.org/10.1109/TIE.2020.3036227
3	Study of Torsional Vibration Bifurcation Characteristics of Direct-Drive Wind Turbine Shaft System	https://doi.org/10.3390/pr10091700
4	Optimal Controller Tuning Technique for a First-Order Process with Time Delay	https://arxiv.org/pdf/2210.08187
5	Impedance Model of PMSG-Based Wind Turbine System and Stability Analysis Based on Routh Criterion	https://doi.org/10.1109/CEEPE62022.2024.10586494
6	Order Reduction of Autonomous Microgrids Using Pade and Routh Approximation	https://doi.org/10.1109/ICSES63445.2024.10762988
7	Approximation of Interval Modelled Higher Order Boost Converter Utilizing Modified Routh-Padé Technique	https://doi.org/10.1109/PEDES56012.2022.10080213
8	Frequency Stability in Modern Power Systems with 100% Renewable Energy Penetration	https://dx.doi.org/10.2139/ssrn.5062014
9	Hybrid intelligent h-AFSA-ANN controller for the SPV-BESS-DG-based DC microgrid integrated system	https://doi.org/10.1007/s00202-023-02130-9
10	Modelling and simulation of wind turbine using MATLAB/Simulink	https://rjpn.org/ijcspub/papers/IJCSP22D1026.pdf
11	Incremental Conductance Algorithm Based On Indirect Control Mode Using An Integrator Controller Tuned by Routh Criterion	https://doi.org/10.1109/SIENR50924.2021.9631913
12	Stability analysis for routh-hurwitz conditions using partial pivot	https://doi.org/10.1088/1742-6596/1341/6/062017
13	Reliability analysis of a grid-connected hybrid renewable energy system using hybrid Monte-Carlo and Newton Raphson methods	https://doi.org/10.3389/fenrg.2024.1435221
14	Integrating Particle Swarm Optimization and Routh-Hurwitz's Theory for Controlling Grid-Connected LCL-Filter Converter	https://doi.org/10.22266/ijies2020.0831.10
15	Grid-connected renewable energy systems flexibility in Norway islands' Decarbonization	https://doi.org/10.1016/j.rser.2023.113658
16	Symmetric properties of Routh–Hurwitz and Schur–Cohn stability criteria	https://doi.org/10.3390/sym14030603
17	Stability analysis and control parameter optimization of multi-VSG parallel grid-connected system	https://doi.org/10.1016/j.epsr.2023.109478
18	Validation of performance evaluation using MATLAB/Simulink model of a PV array	https://doi.org/10.29294/IJASE.6.3.2020.1424-1429

19	A comprehensive review of small-signal stability and power oscillation damping through photovoltaic inverters	https://doi.org/10.3390/en14217372
20	Stability analysis of grid-integrated PV systems	https://doi.org/10.14445/22315381/IJETT-V72I4P106
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23	Modelling and simulation of solar PV and wind hybrid power system using MATLAB/Simulink	https://www.irjet.net/archives/V5/i4/IRJET-V5I4138.pdf
24	Reduction of Interconnected Hybrid Power System Using Direct Truncation and Routh Array Method	https://doi.org/10.1109/ETFG55873.2023.10407619
25	Stability Analysis of a Nonlinear PID Controller	https://doi.org/10.1007/s12555-020-0599-y
26	Inferring PID Parameter Specification for Flight Control Program by Coordinate Search	https://doi.org/10.1145/3728904
27	A Virtual Synchronous Generator Low-Voltage Ride-Through Control Strategy Considering Complex Grid Faults	https://doi.org/10.3390/app15041920