Past inertsiyali sharoitlarda yirik hajmdagi qayta tiklanuvchi energiya manbalari integratsiyalashgan elektr energetika tizimlarining Grid-Forming va Grid-Following boshqaruv usullariga asoslangan barqarorligini baholash

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Dolzarblik: Past inertsiyali qayta tiklanuvchi energiya manbalari integratsiyalangan tizimlarda chastota va kuchlanish barqarorligi muammolari kuchaymoqda.

Maqsad: Ushbu tadqiqotda GFL/GFM inverterlari dinamikasi, virtual inertsiya, ekvivalent tashqi tarmoq va reaktiv quvvat boshqaruviga asoslangan matematik-imitatsion model ishlab chiqildi.

Usullar: Thevenin ekvivalenti, dq-koordinatali inverter boshqaruvi, virtual inertsiya, droop-algoritmlar va parametrik dinamik modellashtirish qo‘llanildi.

Natijalar: GFL ulushi ortishi tizim inertsiyasini kamaytirib, chastota tebranishlarini va barqarorlashish vaqtini oshirdi, GFM agregatlari esa kuchlanish hamda chastota barqarorligini ta’minladi.

Kalit so‘zlar: Qayta tiklanuvchi energiya; GFL inverter; GFM inverter; chastota barqarorligi; kuchlanish barqarorligi; virtual inertsiya; weak grid; dinamik modellashtirish.

Оценка устойчивости крупномасштабных электроэнергетических систем с интегрированными возобновляемыми источниками энергии на основе подходов Grid-Forming и Grid-Following в условиях низкой инерции

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Актуальность: Энергосистемы с высокой долей возобновляемых источников энергии сталкиваются с проблемами устойчивости частоты и напряжения при снижении инерции.

Цель: В работе разработана математико-имитационная модель для оценки устойчивости частоты и напряжения в энергосистемах с ВИЭ на основе динамики GFL/GFM-инверторов, эквивалентной сети, виртуальной инерции и реактивного регулирования.

Методы: Использованы эквивалент Tevenin, dq-моделирование инверторов, виртуальная инерция, droop-алгоритмы и параметрическое динамическое моделирование.

Результаты: Увеличение доли GFL-инверторов снижает эффективную инерцию, усиливает колебания частоты и увеличивает время стабилизации, тогда как GFM-инверторы обеспечивают устойчивое восстановление напряжения и частоты.

Ключевые слова: Интеграция ВИЭ; GFL-инвертор; GFM-инвертор; устойчивость частоты; устойчивость напряжения; виртуальная инерция; слабая сеть; динамическое моделирование

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Grid-Forming and Grid-Following Based Stability Assessment of Large-Scale Renewable Integrated Power Systems Under Low-Inertia Conditions

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Relevance: Low-inertia renewable-integrated power systems face increasing frequency and voltage stability challenges under high penetration of inverter-based generation.
Objective: This study develops a mathematical–simulation model for evaluating frequency and voltage stability in renewable-integrated power systems using GFL/GFM inverter dynamics, equivalent grid characteristics, virtual inertia, and reactive power control under varying renewable penetration scenarios.
Methods: Thevenin-based equivalent modeling, dq-frame inverter control, virtual inertia, droop algorithms, and parametric dynamic simulations were applied.
Results: Increasing GFL penetration reduced effective inertia, enlarged frequency oscillations, and prolonged stabilization time, while GFM units-maintained voltage and frequency recovery stability.

Keywords: renewable integration; GFL inverter; GFM inverter; frequency stability; voltage stability; virtual inertia; weak grid; dynamic modeling.

1. Introduction

The rapid integration of large-scale renewable energy sources into modern electric power systems has significantly transformed conventional grid operation principles. Increasing penetration of inverter-based renewable generation, particularly wind and solar power plants, reduces the contribution of synchronous rotating machines and consequently decreases the overall inertia of the power system. Under such conditions, maintaining frequency and voltage stability becomes one of the most critical technical challenges in modern power engineering.

In traditional power systems, synchronous generators inherently provide rotational inertia and damping characteristics that support transient stability during disturbances. However, renewable energy systems connected through power electronic converters do not naturally contribute to system inertia. As the share of renewable generation increases, frequency deviations become faster, voltage oscillations intensify, and system recovery time becomes longer. Therefore, advanced stability assessment methods and intelligent inverter control strategies are required for reliable operation of low-inertia power systems.

In this study, a mathematical–simulation model of a large-scale renewable integrated power system was developed based on equivalent external grid characteristics. The Point of Interconnection (POI) was selected as the primary analysis node for evaluating voltage, frequency, active power, and reactive power dynamics. The external grid was simplified using the Thevenin equivalent approach, enabling the investigation of strong-grid and weak-grid conditions through Short Circuit Ratio (SCR) variation. The proposed model incorporates Grid-Following (GFL) and Grid-Forming (GFM) inverter control structures, virtual inertia mechanisms, droop-control algorithms, and reactive power support strategies. Frequency dynamics were evaluated using swing-equation-based analysis, while voltage stability was assessed through reactive power balance and Q–V droop control relationships.

The study further investigates the influence of increasing GFL penetration on system dynamic performance while maintaining a constant number of GFM units. The results provide important insights into frequency oscillation behavior, voltage recovery capability, and dynamic stability margins of renewable-dominated power systems [1,2,3].

2. Materials and Methods

The renewable integrated power system was represented through an equivalent external network model based on the Thevenin theorem. In the proposed approach, the entire multi-node transmission system was simplified into an equivalent voltage source and an equivalent series impedance:

$$Z_{eq} = R_{eq} + jX_{eq} \tag{1}$$

where R_{eq} represents active resistance and X_{eq} denotes reactive impedance.

The short-circuit power of the equivalent grid was determined as:

$$S_{sc} = \frac{U_n^2}{|Z_{eq}|} \tag{2}$$

The Short Circuit Ratio (SCR), which characterizes grid stiffness, was calculated using:

$$SCR = \frac{S_{sc}}{S_d} \tag{3}$$

Variation of SCR enabled the simulation of both strong-grid and weak-grid operating conditions. Low SCR values corresponded to weak grids with reduced voltage support capability and increased sensitivity to renewable power fluctuations [4].

At the Point of Interconnection (POI), three-phase voltage and current signals were measured continuously to determine active and reactive power flow behavior. The voltage profile at the POI was analyzed considering equivalent network impedance and renewable generation dynamics.

To evaluate system frequency stability under renewable penetration growth, virtual inertia and droop-control mechanisms were implemented. Frequency dynamics were modeled according to the classical swing equation:

$$2H\frac{d\omega}{dt} = P_m - P_e - D(\omega - \omega_0) \tag{4}$$

where $H$is the inertia constant, $P_m$is the mechanical input power, $P_e$is electrical power, and $D$is the damping coefficient.

The decrease in synchronous generator participation caused effective system inertia reduction, resulting in larger Rate of Change of Frequency values and longer stabilization times.

Voltage stability was evaluated through active and reactive power transmission equations:

$$P = \frac{E_{eq}U}{X_{eq}}\sin\,\delta \tag{5}$$

$$Q = \frac{U(E_{eq}\cos\,\delta - U)}{X_{eq}} \tag{6}$$

The influence of equivalent reactance on voltage profile degradation was investigated under different renewable penetration scenarios.

Reactive power support was controlled using a Q–V droop mechanism:

$$V = V_0 - k_q(Q - Q_0) \tag{7}$$

This approach enabled voltage regulation during transient disturbances and weak-grid operation. The renewable energy subsystem was modeled using a wind power plant equipped with Permanent Magnet Synchronous Machine (PMSM) technology. The aerodynamic power extracted from the turbine was calculated as:

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta)v^3 \tag{8}$$

where $\rho$is air density, $A$is rotor swept area, $C_p$is the power coefficient, $v$is wind speed, $\lambda$is tip-speed ratio, and $\beta$is blade pitch angle [5,6].

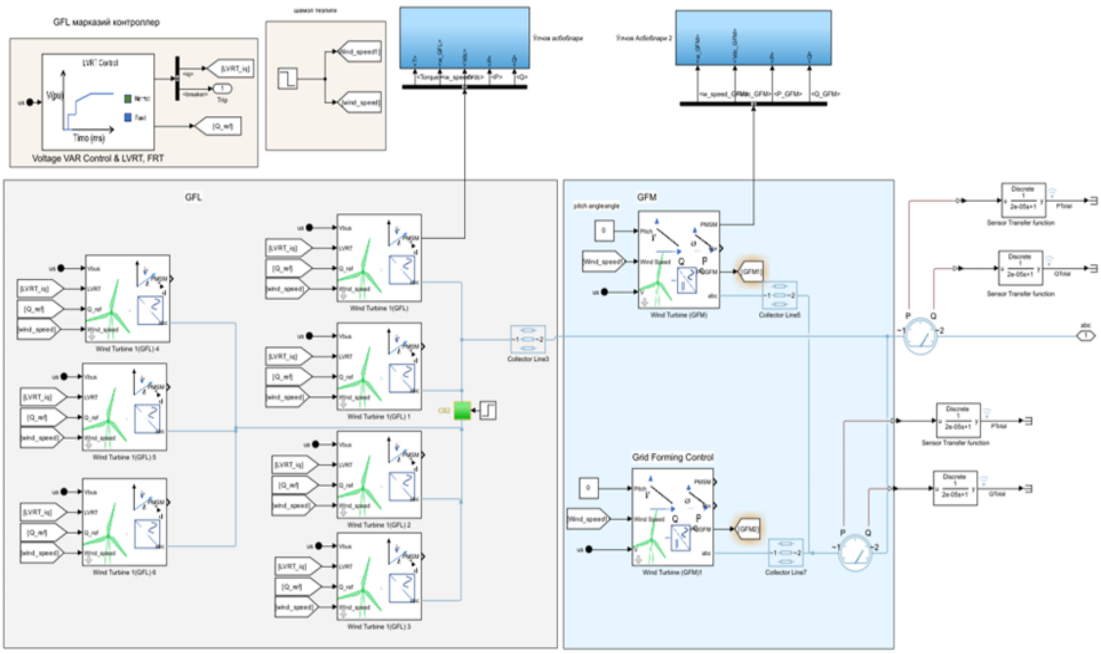

Fig. 1. Mathematical–Simulation Model of Renewable Energy Sources in a Renewable-Integrated Power System (Based on Wind Power Plant)

The turbine mechanical torque was expressed as:

$$T_m = \frac{P_m}{\omega_r} \tag{9}$$

Rotor dynamics were determined through:

$$J\frac{d\omega_r}{dt} = T_m - T_e - D\omega_r \quad (10)$$

where Jrepresents inertia moment and $T_e$is electromagnetic torque.

Active and reactive powers in dq-coordinates were evaluated using:

$$P = \frac{3}{2}(v_d i_d + v_q i_q), Q = \frac{3}{2}(v_q i_d - v_d i_q) \quad (11)$$

The simulation model additionally incorporated Low Voltage Ride Through (LVRT), Voltage VAR Control, PLL synchronization, GFL control, and GFM control algorithms (Fig. 1).

The simulation parameters were selected close to real operating conditions to improve practical applicability of the model (Table 1).

The number of GFL units was varied as 1, 3, 5, and 7, while the number of GFM units remained constant.

3. Result and discussion

Simulation results demonstrated that increasing penetration of GFL-based renewable generation significantly affects system dynamic stability.

At low renewable penetration levels, the system frequency deviation remained limited, and recovery to nominal frequency occurred rapidly. In the scenario with one GFL unit, frequency oscillation varied between approximately 49.96 Hz and 50.08 Hz, while stabilization occurred within 2–3 seconds.

Table 1. Main Parameters of the Developed Mathematical–Simulation Model for Renewable Integrated Power System Stability Analysis

Parameter	Symbol	Value
Nominal frequency	f_n	50 Hz
Nominal voltage	V_n	1 p.u.
Equivalent impedance	Z_{eq}	0,15–0,25 p.u.
Short Circuit Ratio	SCR	3–5
Single GFL unit power	S_{GFL}	≈20 MVA
Power factor	cosφ	0.95
Reactive power limit	Q_{max}	±0,3 p.u.
PLL time constant	T_{PLL}	0,02–0,03 s
Number of GFM units	–	2

However, increasing the number of GFL units reduced effective system inertia. In the scenario with seven GFL units, the maximum frequency deviation increased considerably. Frequency reached approximately 50,20 Hz during transient response and dropped to nearly 49,78 Hz before stabilization. The settling time increased to approximately 6–8 seconds.

These results clearly indicate that high penetration of GFL converters weakens frequency support capability because such converters follow existing grid frequency rather than forming it independently (Fig. 2).

Voltage stability analysis showed relatively stable voltage magnitude behavior due to the presence of GFM units and reactive power control mechanisms. Although voltage dips became deeper as renewable penetration increased, all scenarios maintained acceptable voltage recovery characteristics.

For example, the minimum voltage magnitude values observed were approximately:

- 0,9975 p.u. for 1 GFL;
- 0,9955 p.u. for 3 GFL;
- 0,9930 p.u. for 5 GFL;
- 0,9910 p.u. for 7 GFL.

Despite deeper transient voltage reductions, the system successfully restored voltage magnitude close to 1.0 p.u. within several seconds due to GFM inverter support and Q–V droop control [7,8].

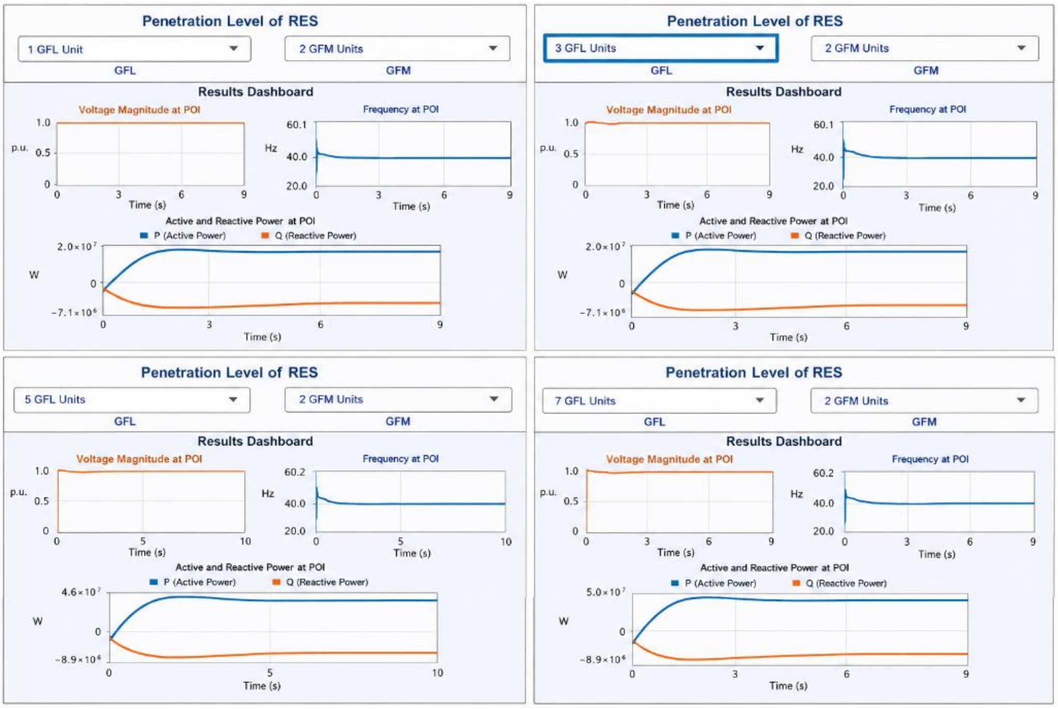

Fig. 2. Dynamics of Voltage and Frequency Stability at the POI Under Varying Numbers of GFL Units in Renewable Energy Integrated Power Systems

The results additionally confirmed that GFM inverters play a crucial role in renewable-dominated power systems. Unlike GFL converters, GFM units actively establish voltage and frequency references and provide virtual inertia support during disturbances. Consequently, systems with GFM participation exhibited improved damping characteristics and better transient recovery performance. The influence of renewable penetration on active and reactive power dynamics was also observed. Increasing renewable penetration caused higher reactive power exchange requirements and larger active power fluctuations at the POI. The obtained results are summarized in Table 2.

Table 2. Frequency and Voltage Stability Results at POI

Scenario	**S1**	**S2**	**S3**	**S4**
Number of GFL units	1	3	5	7
Number of GFM units	2	2	2	2
Stable voltage (p.u.)	≈1	≈1	≈1	≈0.99–1
Initial frequency (Hz)	≈50,20	≈50.25	≈50.30	≈50.35
Minimum frequency (Hz)	≈49,95	≈49,90	≈49,85	≈49,80
Stable frequency (Hz)	≈50	≈50	≈50	≈50
Stable active power (W)	$\approx 1{,}9\times 10^7$	$\approx 2{,}1\times 10^7$	$\approx 4\times 10^7$	$\approx 5\times 10^7$
Stable reactive power (W)	$\approx -6{,}0\times 10^6$	$\approx -6{,}5\times 10^6$	$\approx -7{,}5\times 10^6$	$\approx -8\times 10^6$

The analysis further showed that dynamic stability margins decrease considerably as GFL penetration rises. This reduction is mainly associated with lower inertia contribution, weaker synchronization capability, and increased sensitivity to network impedance (Fig. 3).

Overall, the developed mathematical–simulation framework successfully demonstrated the interaction between renewable generation, equivalent grid impedance, inverter control structures, and dynamic stability performance [9,10].

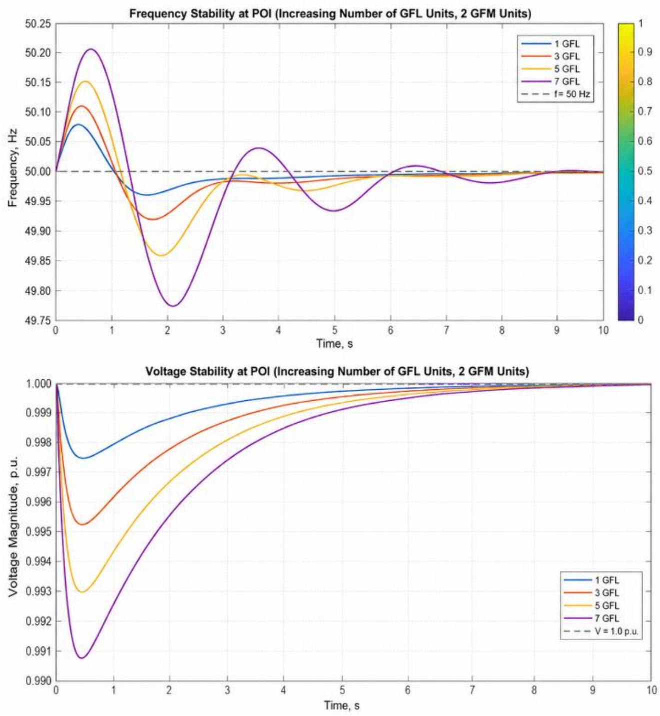

Fig. 3. Impact of Renewable Energy Integration on Frequency and Voltage Stability in the Power System

Conclusions. A mathematical–simulation framework for large-scale renewable integrated power systems was developed based on equivalent external grid characteristics. The study demonstrated that increasing penetration of Grid-Following renewable units significantly decreases effective system inertia, leading to larger frequency oscillations and longer stabilization times.

The results confirmed that Grid-Forming inverters substantially improve system dynamic performance through virtual inertia support and voltage–frequency regulation capabilities. Reactive power compensation and Q–V droop control effectively maintained voltage stability under weak-grid conditions.

The proposed model can be used for future investigation of low-inertia renewable power systems, intelligent inverter coordination, and optimal GFL/GFM ratio selection for improving frequency and voltage stability.

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