



Systematic Analysis of Technical Problems Arising During the Integration of Renewable Energy Sources into the Power Grid

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ABSTRACT

This article presents a revised systematic technical analysis of the main problems arising during the integration of renewable energy sources (RES) into electric power grids. The study focuses on variable solar photovoltaic (PV) and wind generation, inverter-based connection, reduction of system inertia, frequency stability, voltage regulation, reactive power balance, harmonic distortion, short-circuit strength and relay protection selectivity. In response to the need for a stronger quantitative basis, the paper combines classical power-system equations with recent literature on grid-forming inverters, synthetic inertia, weak-grid operation and smart inverter functions. The scientific novelty of the study is not the derivation of new equations, but the integration of these known indicators into a single operational-control framework that maps the chained interaction between inertia, rate of change of frequency (RoCoF), short-circuit ratio (SCR), voltage control, total harmonic distortion (THD), protection coordination and Battery Energy Storage System (BESS) support. A sample calculation is also introduced to demonstrate how a reduction in equivalent inertia increases RoCoF after a generation outage and how fast frequency response (FFR) can mitigate the effect. The results show that reliable integration of high RES shares requires grid reinforcement, flexible generation, BESS, grid-forming inverters, adaptive protection and updated grid codes.

Keywords: Inertia; Rate of Change of Frequency; Grid-Forming Inverter; Synthetic Inertia; Short-Circuit Ratio; Harmonic Distortion; Supervisory Control and Data Acquisition

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1. INTRODUCTION

The large-scale integration of renewable energy sources (RES) into electric power systems is one of the key directions of the global energy transition. Solar photovoltaic (PV) and wind power plants contribute to the reduction of fuel dependence and greenhouse-gas emissions, while also creating new requirements for grid planning, operational flexibility and system security (IEA, 2023; IRENA, 2018). In many countries, renewable generation is being connected faster than transmission and distribution networks can be reinforced. This creates a mismatch between generation development and grid readiness, which may result in congestion, curtailment, voltage violations and reduced operational security.

Traditional power systems have historically been designed around synchronous machines. Such machines naturally provide rotating inertia, short-circuit current contribution, voltage support and primary frequency response, all of which are essential for maintaining power-system stability (Kundur, 1994). By contrast, solar photovoltaic power plants and modern wind turbines are usually connected to the grid through power-electronic converters. Their dynamic behaviour is therefore strongly influenced by inverter control algorithms, current limits, phase-locked loop performance, grid strength and communication with supervisory control systems. As a result, the increasing share of inverter-based resources changes not only the generation mix, but also the physical and control characteristics of the electric power system.

The current state of the art shows that renewable integration problems are increasingly analysed through the concepts of low-inertia operation, grid-forming control, synthetic inertia, fast frequency response (FFR) and smart inverter functions. Recent studies show that grid-forming inverters can improve frequency and voltage support in inverter-dominated systems by establishing voltage and frequency references rather than merely following existing grid conditions (Huang et al., 2023a; Rangarajan et al., 2024; Rahman et al., 2024). Other studies emphasize adaptive inertia control, virtual synchronous generator strategies and the dynamic interaction between inverter control, weak-grid conditions and reactive power compensation (Huang et al., 2023b; Liu et al., 2024; Zhang et al., 2023). These developments indicate that renewable integration should be assessed not only by installed RES capacity, but also by the ability of the grid to maintain frequency, voltage, power quality and protection selectivity under disturbances.

Despite extensive research, many practical studies still evaluate renewable integration challenges separately: inertia is discussed in relation to frequency stability; voltage is analysed through reactive power; power quality is treated through harmonic distortion; and protection is assessed through fault-current levels. However, in real networks these indicators are interdependent. For example, a low short-circuit ratio (SCR) can worsen voltage stability, reduce the reliability of inverter synchronization, increase harmonic sensitivity and complicate protection coordination. Similarly, low inertia can increase the rate of change of frequency (RoCoF), which may trigger under-frequency load shedding or inverter protection unless FFR is available. Therefore, a systematic framework is required to relate these indicators to one another and to connect analytical expressions with operational-control measures.

The main objective of this study is to systematize the technical problems arising during RES integration into power grids and to identify the key quantitative indicators used for their assessment. The study addresses the following research questions: (i) which technical parameters most strongly influence secure RES integration; (ii) how does the reduction of synchronous inertia affect RoCoF and frequency stability; (iii) how do grid strength, voltage regulation, harmonic distortion and protection coordination interact in weak networks; and (iv) what role can grid-forming inverters, synthetic inertia and battery energy storage systems (BESS) play in mitigating these problems?

Methodologically, the paper combines analytical modelling, structured literature review and comparative technical assessment. Classical equations are used for active and reactive power balance, swing dynamics, RoCoF, voltage drop, total harmonic distortion (THD), short-circuit power, SCR and BESS state of charge (SOC). These expressions are then interpreted together with recent studies and international standards, including IEEE Std 1547-2018, IEEE Std 519-2022, NERC guidance on inverter-based resources and recent research on grid-forming inverter technologies (IEEE, 2018; IEEE, 2022; NERC, 2017; Pohl and McKenna, 2024).

The contribution of this paper to the existing literature is threefold. First, it integrates the main technical indicators of renewable integration into a single operational-control framework, rather than treating them as isolated problems. Second, it adds threshold-oriented interpretation to the indicators, including SCR, THD, RoCoF and voltage-control functions. Third, it introduces a simple hypothetical inertia case study that demonstrates the instantaneous impact of lower system inertia on RoCoF and illustrates the mitigating effect of FFR. The remainder of the paper is structured as follows: Section 2 presents the literature review; Section 3 presents the model specification, analytical indicators and data references; Section 4 describes the methodology; Section 5 discusses the results, including quantitative thresholds and the sample calculation; and Section 6 provides the conclusion.

2. LITERATURE REVIEW

The literature on renewable energy integration combines classical power-system stability theory, power-quality analysis and newer research on inverter-dominated grids. Classical references explain that synchronous machines provide inertia, fault-current contribution and voltage support, which traditionally formed the technical basis of frequency stability, protection coordination and voltage regulation in transmission and distribution systems (Kundur, 1994; Bollen, 2000; Masters, 2013).

Institutional studies also emphasize that renewable deployment must be accompanied by grid reinforcement, flexibility resources and updated operational practices. The International Energy Agency (IEA, 2023) highlights the role of modern electricity networks in secure energy transitions, while the International Renewable Energy Agency (IRENA, 2018) identifies power-system flexibility as a necessary condition for integrating variable renewable generation.

A large group of studies focuses on low-inertia operation and frequency stability. Fernández-Guillamón et al. (2020) reviewed inertia and frequency-control strategies in systems with high renewable shares, and Tayyebi et al. (2020) compared the frequency-stability behaviour of synchronous machines and grid-forming power converters. These works show that the reduction of synchronous inertia increases the importance of RoCoF assessment, fast frequency response and inverter-based grid-support functions.

Recent research has shifted attention toward grid-forming inverters, virtual synchronous generator control and adaptive inertia strategies. Huang et al. (2023a, 2023b), Liu et al. (2024), Rahman et al. (2024), Rangarajan et al. (2024), Tina et al. (2024) and Xu et al. (2023) show that advanced inverter controls can support frequency and voltage stability, but their performance depends on grid strength, control parameters and interaction with weak-grid conditions.

Standards and grid-code-oriented studies provide practical screening limits for renewable interconnection. IEEE Std 1547-2018 addresses distributed energy resource interconnection and ride-through functions, IEEE Std 519-2022 provides harmonic-control requirements, and NERC guidance documents discuss inverter-based resources under low short-circuit strength conditions. These sources confirm that renewable integration should be assessed through a combined view of frequency, voltage, short-circuit strength, harmonics, protection and control-system behaviour (IEEE, 2018; IEEE, 2022; NERC, 2017; NERC, 2023; Pohl and McKenna, 2024).

3. MODEL SPECIFICATION AND DATA

The technical problems associated with renewable energy integration can be grouped into several interrelated categories: variability of generation, reduction of system inertia, frequency stability, voltage regulation, reactive power balance, power quality, short-circuit behavior, relay protection coordination, transmission constraints and the need for energy storage. The sections below explain these issues and present the principal analytical indicators used for their assessment.

3.1. Variability of generation and active power balance

In an electric power system, generation and consumption must be balanced at every instant. The general active power balance can be expressed as follows:

$$\sum P_G + \sum P_{RES} + P_{BESS} - P_L - P_{loss} = 0 \quad (1)$$

where (P_G) is the active power of conventional generation sources, MW; (P_{RES}) is the active power of RES, MW; (P_{BESS}) is the active power of the BESS, MW; (P_L) is the load demand, MW; and (P_{loss}) represents network losses, MW.

The simplified output power of a PV power plant may be expressed as:

$$P_{PV} = P_{STC} \cdot \frac{G}{G_{STC}} \cdot [1 + \gamma(T_c - 25)] \cdot \eta_{inv} \quad (2)$$

where (P_{PV}) is the actual PV output power, kW; (P_{STC}) is the module power under standard test conditions, kW; (G) is the actual solar irradiance, W/m^2 ; (G_{STC}) is the standard irradiance, usually $1000 W/m^2$; (γ) is the temperature coefficient, $1/^\circ C$; (T_c) is the cell or module temperature, $^\circ C$; and (η_{inv}) is the inverter efficiency.

For a wind turbine, the output power depends mainly on wind speed and can be represented in a simplified piecewise form:

$$P_W = \begin{cases} 0, & v < v_{ci} \\ P_r \cdot \frac{v^3 - v_{ci}^3}{v_r^3 - v_{ci}^3}, & v_{ci} \leq v < v_r \\ P_r, & v_r \leq v \leq v_{co} \\ 0, & v > v_{co} \end{cases} \quad (3)$$

where (v_{ci}) is the cut-in wind speed, (v_r) is the rated wind speed, (v_{co}) is the cut-out wind speed and (P_r) is the rated turbine power.

Equations (1)-(3) show that renewable generation depends directly on meteorological parameters. Cloud movement, solar irradiance fluctuations, temperature changes and wind-speed variations can cause rapid changes in power output. Consequently, short-term forecasting systems, balancing reserves, flexible generation and energy storage are required for stable operation (IEA, 2023; IRENA, 2018; Masters, 2013).

3.2. Frequency stability and reduction of system inertia

When a mismatch occurs between generation and load, the system frequency deviates from its nominal value. In conventional systems, the rotating masses of synchronous generators slow down the frequency change and provide an inherent inertial response. This dynamic behavior can be described by the simplified swing equation:

$$\frac{2H}{f_0} \cdot \frac{df}{dt} = P_m - P_e - D\Delta f \quad (4)$$

where (H) is the inertia constant, s; (f_0) is the nominal frequency, Hz; (df/dt) is the rate of frequency change, Hz/s; (P_m) is the mechanical input power; (P_e) is the electrical output power; (D) is the load damping coefficient; and (f) is the frequency deviation.

RoCoF can be approximated as:

$$RoCoF = \frac{df}{dt} \approx \frac{\Delta P \cdot f_0}{2H_{sys}S_{base}} \quad (5)$$

where (P) is the sudden power imbalance, MW; ($H_{\{sys\}}$) is the equivalent system inertia, s; and ($S_{\{base\}}$) is the system base power, MVA.

As the share of inverter-based renewable generation increases, the number of online synchronous machines may decrease. This reduces ($H_{\{sys\}}$). According to equation (5), a lower value of ($H_{\{sys\}}$) leads to a higher RoCoF for the same power imbalance. This can cause faster frequency deviations, earlier operation of under-frequency load shedding schemes and increased risk of instability (Fernández-Guillamón et al., 2020; NREL, 2021; Tayyebi et al., 2020).

One technical measure is the use of FFR and droop-based inverter control. The active-power response of an inverter can be written as:

$$\Delta P = -K_f(f - f_0) \quad (6)$$

where (K_f) is the frequency-droop coefficient. With this control law, the inverter increases active power when frequency decreases and reduces active power when frequency increases. In addition, grid-forming inverter technologies can provide voltage and frequency reference functions and are considered important for future systems with high shares of inverter-based resources (Huang et al., 2023b; NREL, 2020; Rangarajan et al., 2024; Tina et al., 2024).

3.3. Voltage regulation and reactive power balance

Voltage stability is one of the most important technical issues in renewable integration. The general reactive power balance can be written as:

$$\sum Q_G + \sum Q_{RES} + Q_{comp} - Q_L - Q_{loss} = 0 \quad (7)$$

where (Q_G) is the reactive power of conventional sources; ($Q_{\{RES\}}$) is the reactive power of RES units; ($Q_{\{comp\}}$) is the reactive power of compensation devices; (Q_L) is the reactive load; and ($Q_{\{loss\}}$) is the reactive power loss in the network.

In radial distribution networks, voltage drop can be approximately calculated as:

$$\Delta U \approx \frac{R \cdot P + X \cdot Q}{U_n} \quad (8)$$

where (R) is the line resistance, Ω ; (X) is the line reactance, Ω ; (P) is active power flow, W; (Q) is reactive power flow, var; and (U_n) is the nominal voltage, V.

A high concentration of distributed PV generation may reverse the direction of power flow during daytime and increase the voltage at remote points of the feeder. In this case, inverter-based Volt-VAR control becomes important. A simplified Volt-VAR control law may be expressed as:

$$\Delta Q = -K_v(U - U_0) \quad (9)$$

where (K_v) is the voltage-control coefficient, (U) is the measured voltage and (U_0) is the reference voltage.

The reactive power capability of an inverter is limited by its apparent power rating:

$$S^2 = P^2 + Q^2 \quad (10)$$

This equation shows that when the inverter operates near its maximum active power output, the remaining margin for reactive power support decreases. Therefore, inverter sizing, power factor capability, reactive power range and grid-code requirements should be assessed during the design stage. Recent studies also show that voltage-control actions in weak grids may interact with inverter frequency control, which confirms that voltage and frequency stability must be evaluated jointly (Murzakhanov et al., 2022; Zhang et al., 2023; Xu et al., 2023).

3.4. Power quality and harmonic distortion

Inverter-based generation can affect power quality. The most common issues include harmonic distortion, flicker, voltage unbalance, switching transients and resonance. These effects are especially important in weak grids and long radial feeders, where the interaction between inverter controls and network impedance may increase distortion levels (Bollen, 2000). THD for current can be calculated as:

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + \dots + I_n^2}}{I_1} \cdot 100\% \quad (11)$$

where (I_1) is the rms value of the fundamental current component and (I_2, I_3, \dots, I_n) are the rms values of higher-order harmonics.

The equivalent expression for voltage is:

$$THD_U = \frac{\sqrt{U_2^2 + U_3^2 + \dots + U_n^2}}{U_1} \cdot 100\% \quad (12)$$

An increase in harmonic distortion may lead to additional heating in transformers and cables, resonance in capacitor banks, incorrect operation of protection devices and malfunction of sensitive electronic equipment. IEEE Std 519-2022 provides voltage distortion limits at the point of common coupling (PCC) and is therefore a useful quantitative reference for evaluating renewable-energy interconnection studies (IEEE, 2022).

3.5. Short-circuit strength and relay protection issues

The integration of RES affects short-circuit regimes. Conventional synchronous generators can contribute high fault currents during short circuits. Inverter-based resources, however, usually limit their fault current to controlled values close to their rated current. The short-circuit power at a connection point can be expressed as:

$$S_{sc} = \sqrt{3} \cdot U_n \cdot I_{sc} \quad (13)$$

where (S_{sc}) is the short-circuit power, MVA; (U_n) is the nominal voltage, kV; and (I_{sc}) is the short-circuit current, kA.

The SCR is used to evaluate the strength of the network at the point of connection:

$$SCR = \frac{S_{sc}}{P_{RES}} \quad (14)$$

where (P_{RES}) is the active power of the connected RES. A low SCR indicates a weak-grid condition. In weak grids, inverter synchronization, voltage stability, harmonic resonance and transient performance become more critical (NERC, 2017; Yu et al., 2024).

Many existing protection schemes were designed for unidirectional power flow and high short-circuit currents. When distributed renewable generation is connected to distribution networks, bidirectional power flow may occur. This can affect the selectivity of overcurrent protection and complicate fault-location functions. Directional relays, differential protection, communication-assisted protection, adaptive protection algorithms and real-time supervisory control and data acquisition (SCADA)/energy management system (EMS) integration are therefore required. The growing reliability concern associated with inverter-based resource performance has also led to new regulatory and standardization efforts addressing fault ride-through (FRT), disturbance monitoring and post-event validation (NERC, 2023; Pohl and McKenna, 2024).

3.6. Role of BESS and grid-forming control

BESS are important flexibility resources in grids with high renewable penetration. BESS can support active power balance, frequency regulation, voltage control, peak shaving and congestion management. Such flexibility resources are widely recognized as key enablers of renewable integration (IRENA, 2018). The SOC of a battery can be written as:

$$SOC(t) = SOC(t - 1) + \frac{\eta_{ch} P_{ch} \Delta t}{E_{nom}} - \frac{P_{dis} \Delta t}{\eta_{dis} E_{nom}} \quad (15)$$

where (SOC) denotes battery SOC; (P_{ch}) is the charging power; (P_{dis}) is the discharging power; (η_{ch}) and (η_{dis}) are the charging and discharging efficiencies; (E_{nom}) is the nominal energy capacity; and (t) is the time interval.

The correct sizing of BESS requires assessment of energy capacity, power rating, C-rate, cycle life, degradation, fire safety, cooling requirements and control algorithms. In high-renewable systems, BESS should not be considered only as an energy-shifting device; it is also a fast dynamic resource for grid support. When combined with grid-forming inverter control, BESS can provide synthetic inertia, frequency reference support, black-start capability and voltage-forming functions (Huang et al., 2023a; Liu et al., 2024; Rahman et al., 2024).

4. METHODOLOGY

The study uses systematic analysis, analytical modelling and comparative technical assessment. The impact of RES on the power grid is evaluated according to technical indicators commonly used in grid planning, interconnection assessment and distributed energy resource (DER) studies (IEEE, 2018; Kundur, 1994; NERC, 2017). These indicators include active power balance and generation variability; frequency deviation and RoCoF; reactive power balance and voltage profile; THD and power quality; short-circuit strength and SCR; relay protection selectivity; and the balancing role of BESS.

The methodological approach is based on evaluating renewable integration not by a single parameter, but through the interaction of active power, reactive power, frequency, voltage, power quality and protection-system performance. This approach makes it possible to identify not only local connection problems, but also system-wide operational risks. The study also reviews recent research from 2022-2024 on grid-forming inverters, adaptive inertia, virtual synchronous generator control, weak-grid PV stability and inverter-based resource performance (Huang et al., 2023b; Liu et al., 2024; Rangarajan et al., 2024; Tina et al., 2024; Zhang et al., 2023).

Table 1 expands the original indicator list by adding practical threshold values or screening limits. These values should not be interpreted as universal design limits for every grid. They are planning references that must be checked against the applicable national grid code, interconnection agreement, equipment specification and system-operator requirements.

Table 1. Main technical indicators, screening thresholds and interpretation for renewable energy integration

Indicator	Symbol	Unit	Screening threshold or reference value	Technical interpretation
Active power balance	P	MW	Real-time balance required	A sustained mismatch causes frequency deviation.
Reactive power balance	Q	MVAr	Required by grid code and inverter capability curve	Insufficient reactive support causes voltage instability.
Rate of change of frequency	RoCoF	Hz/s	No universal limit; many grid-code studies screen values above about 0.5-1.0 Hz/s as critical	Higher RoCoF indicates lower inertia and need for fast frequency response.
Short-circuit ratio	SCR	-	SCR > 3 strong; SCR 2-3 weak; SCR < 2 very weak, as a rule-of-thumb screening criterion	Low SCR increases voltage, synchronization, harmonics and protection risks.
Voltage THD at PCC	THD_U	%	IEEE Std 519-2022: 5% for 1 kV < V ≤ 69 kV; 8% for V ≤ 1 kV	Higher THD may cause overheating, resonance and equipment malfunction.
Voltage regulation function	Volt-VAR	-	IEEE Std 1547-2018 requires DER voltage/reactive power capabilities by category	Enables autonomous inverter support for feeder voltage control.
Frequency-watt response	f-W	-	Required or recommended depending on DER category and local grid code	Supports active-power response during abnormal frequency conditions.
Battery state of charge	SOC	%	Project-specific; practical operation often maintains reserve margins	Defines available energy for balancing and fast dynamic support.
Fault ride-through	FRT	-	IEEE Std 1547-2018 and local grid codes define voltage/frequency ride-through categories	Prevents widespread disconnection of DER during disturbances.

Source: Author's own compilation based on International Energy Agency (IEA, 2023), International Renewable Energy Agency (IRENA, 2018), Institute of Electrical and Electronics Engineers (IEEE, 2018, 2022), and North American Electric Reliability Corporation (NERC, 2017, 2023).

5. RESULTS AND DISCUSSION

The systematic analysis shows that a high share of RES affects the traditional operating principles of power systems in several directions.

First, the variability of solar and wind generation complicates active power balancing. Equations (1)-(3) show that renewable output depends on meteorological parameters and therefore introduces additional uncertainty into the load-generation balance. This makes short-term forecasting, flexible resources and balancing reserves essential. However, the balancing requirement should not be considered only an energy problem; it is also a stability problem because the instantaneous mismatch directly affects frequency.

Second, the reduction of system inertia creates a significant frequency-stability risk. According to equation (5), when equivalent system inertia decreases, the RoCoF increases for the same disturbance. This requires faster and more coordinated operation of automatic protection and control systems. Grid-forming inverters, synthetic inertia and BESS-based FFR are among the most important measures for mitigating this risk. Recent studies on adaptive inertia and virtual synchronous generator control show that fixed inertia parameters may not be optimal under all operating conditions; adaptive and nonlinear inertia control can improve the compromise between nadir reduction, settling time and stability margin (Huang et al., 2023b; Liu et al., 2024).

Third, reactive power balance and voltage regulation become more complex. Equation (8) shows that voltage in radial networks depends on both active and reactive power flows. High PV penetration may lead to reverse power flow and overvoltage, especially in distribution feeders. Therefore, Volt-VAR and Volt-Watt functions, automatic voltage regulators, transformer tap changers, capacitor banks, STATCOM/SVC devices and proper inverter sizing are needed. The recent literature also emphasizes that weak-grid voltage regulation can interact with frequency-control dynamics and inverter synchronization (Zhang et al., 2023; Xu et al., 2023).

Fourth, power quality becomes a critical operational issue. Equations (11) and (12) provide the basis for calculating current and voltage harmonic distortion. A high number of inverters, weak-grid conditions and resonance with compensation devices can increase THD. This may reduce equipment lifetime and cause malfunction of sensitive loads and protection devices. The thresholds in Table 1 therefore make the analysis more useful for planning because they connect the analytical definition of THD with an internationally recognized reference limit (IEEE, 2022).

Fifth, short-circuit strength and protection coordination must be reassessed. The SCR indicator in equation (14) characterizes the strength of the grid at the renewable connection point. A low SCR may cause instability of inverter control systems, poor voltage recovery and incorrect protection operation. In such cases, traditional overcurrent protection may not be sufficient, and adaptive or communication-assisted protection should be applied. Recent work on multiple renewable short-circuit ratio further shows that system strength should be assessed not only for a single generator, but also for areas with several adjacent inverter-based resources (Yu et al., 2024).

Sixth, BESS are one of the main technical enablers of high renewable penetration. Equation (15) describes BESS SOC dynamics and shows that storage can participate in both energy balancing and fast dynamic support. However, the practical application of BESS requires detailed techno-economic assessment, including capacity, power rating, degradation and safety requirements. From an operational-control perspective, the value of BESS increases when it is integrated with grid-forming inverter control, because the same asset can support energy shifting, frequency stability, voltage control and black-start capability.

5.1. Hypothetical case study: effect of inertia reduction on RoCoF

To illustrate the practical meaning of equation (5), consider a simplified 50 Hz system with ($S_{\text{base}}=1000$) MVA. Assume that a generation unit of 100 MW is suddenly disconnected, creating ($P=100$) MW. In the first case, the equivalent system inertia is ($H_{\text{sys}}=4$) s. The initial RoCoF is:

$$RoCoF_1 = \frac{100 \cdot 50}{2 \cdot 4 \cdot 1000} = 0.625 \text{ Hz/s} \quad (16)$$

If renewable penetration increases and fewer synchronous machines remain online, the equivalent inertia may fall to ($H_{\text{sys}}=2$) s. Under the same disturbance, the RoCoF becomes:

$$RoCoF_2 = \frac{100 \cdot 50}{2 \cdot 2 \cdot 1000} = 1.25 \text{ Hz/s} \quad (17)$$

This simple calculation shows that halving the equivalent inertia doubles the RoCoF for the same power imbalance. If BESS or a grid-forming inverter provides 50 MW of FFR, the net imbalance is reduced to 50 MW. In the low-inertia case, the initial RoCoF is then:

$$RoCoF_3 = \frac{50 \cdot 50}{2 \cdot 2 \cdot 1000} = 0.625 \text{ Hz/s} \quad (18)$$

The result demonstrates that FFR can partially compensate for reduced synchronous inertia. It also shows why inertia, BESS sizing, inverter control and protection settings must be studied together. If the RoCoF is high, frequency may cross protection thresholds before slower reserves respond. Therefore, the operational sequence should include disturbance detection, immediate inertial or

synthetic inertial response, fast active-power support, primary frequency response and slower balancing actions. This chained perspective is the main distinction of the present review from studies that consider each technical parameter separately.

5.2. Scientific novelty and systematic contribution

The equations used in this article are classical and widely known in power-system engineering. Therefore, the novelty of this paper does not lie in proposing a new mathematical equation. Instead, the novelty lies in the systematic mapping of classical indicators into a single practical framework for renewable integration assessment. In this framework, active-power imbalance affects frequency; reduced inertia increases RoCoF; low SCR worsens inverter synchronization and voltage recovery; voltage-control actions influence reactive-power balance and, in weak grids, may interact with frequency-control loops; harmonic distortion affects equipment and protection performance; and BESS/grid-forming inverters provide both energy and dynamic stability support.

This integrated mapping provides an operational-control perspective that is particularly useful for planning renewable projects in weak or medium-strength networks. It supports a step-by-step assessment sequence: first, determine grid strength and short-circuit level; second, evaluate active and reactive power flows; third, assess frequency response and inertia adequacy; fourth, perform harmonic and resonance studies; fifth, verify protection selectivity and ride-through requirements; and sixth, size BESS and inverter functions for both energy and stability services. This approach distinguishes the present review from conventional descriptions that list renewable integration challenges without explicitly linking their cause-effect relationships.

6. CONCLUSION

The integration of RES into the power grid is essential for decarbonization and energy security, but it requires comprehensive technical preparation. The analysis carried out in this article demonstrates that the main technical problems are related to generation variability, reduction of system inertia, frequency stability, voltage regulation, reactive power balance, harmonic distortion, changes in short-circuit power and relay protection selectivity.

The results show that reliable integration of high RES shares requires the following technical measures: load-flow, short-circuit and harmonic studies at the connection point; implementation of Volt-VAR, Volt-Watt, frequency-watt and FRT functions; use of grid-forming and synthetic-inertia-capable inverters; application of BESS as balancing resources; deployment of adaptive and directional relay protection; real-time monitoring and control through SCADA/EMS systems; and updating grid codes in line with the technical characteristics of RES (IEEE, 2018; NERC, 2023; NREL, 2020).

The scientific conclusion is that renewable integration is not only a matter of increasing generation capacity, but a transformation of the entire electric power system in terms of stability, flexibility and controllability. During technical planning, active power balance, reactive power control, frequency response, SCR, THD and BESS SOC should therefore be assessed together rather than separately. The hypothetical calculation confirms that the reduction of system inertia can substantially increase RoCoF, while FFR from BESS or grid-forming inverters can reduce the effective imbalance and improve dynamic security. This confirms the need for integrated planning methods that combine classical power-system indicators with modern inverter-based control functions.

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REFERENCES

- Bollen, M. H. J. (2000). *Understanding power quality problems: Voltage sags and interruptions*. IEEE Press.
- Fernández-Guillamón, A., Gómez-Lázaro, E., Muljadi, E., and Molina-García, A. (2020). Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. *Renewable and Sustainable Energy Reviews*, *115*, 109369.
- Huang, L., Wu, C., Zhou, D., Chen, L., Pagnani, D., and Blaabjerg, F. (2023a). Challenges and potential solutions of grid-forming converters applied to wind power generation system—An overview. *Frontiers in Energy Research*, *11*, 1040781. <https://doi.org/10.3389/fenrg.2023.1040781>
- Huang, R., Dong, C., Wu, Z., Quan, X., Wang, Z., Sun, T., and Hou, K. (2023b). A sigmoid-based adaptive inertia control strategy for grid-forming inverter to enhance frequency stability. *Frontiers in Energy Research*, *11*, 1095610. <https://doi.org/10.3389/fenrg.2023.1095610>
- Institute of Electrical and Electronics Engineers (IEEE). (2018). IEEE Std 1547-2018: IEEE standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces. IEEE.
- Institute of Electrical and Electronics Engineers (IEEE). (2022). IEEE Std 519-2022: IEEE recommended practice and requirements for harmonic control in electric power systems. IEEE.
- International Energy Agency (IEA). (2023). Electricity grids and secure energy transitions. <https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions>. Accessed on 18 June 2026.
- International Renewable Energy Agency (IRENA). (2018). Power system flexibility for the energy transition. <https://www.irena.org/publications/2018/Nov/Power-system-flexibility-for-the-energy-transition>. Accessed on 18 June 2026.
- Kundur, P. (1994). *Power system stability and control*. McGraw-Hill.
- Liu, D., Li, J., Zhang, X., Wang, Y., and Chen, H. (2024). Improved VSG strategy of grid-forming inverters for enhancing power-grid integration capability. *Frontiers in Energy Research*, *12*, 1331024. <https://doi.org/10.3389/fenrg.2023.1331024>
- Masters, G. M. (2013). *Renewable and efficient electric power systems*. 2nd Edition. Wiley-IEEE Press.
- Murzakhanov, I., Gupta, S., Chatzivasileiadis, S., and Kekatos, V. (2022). Optimal design of Volt/VAR control rules for inverter-interfaced distributed energy resources. *IEEE Transactions on Smart Grid*. Advance online publication.
- National Renewable Energy Laboratory (NREL). (2020). Research roadmap on grid-forming inverters. <https://www.nrel.gov/docs/fy21osti/73476.pdf>. Accessed on 18 June 2026.
- National Renewable Energy Laboratory (NREL). (2021). Final technical report: Stabilizing the power system in 2035 and beyond: Evolving from grid-following to grid-forming distributed inverter controllers. <https://www.nrel.gov/docs/fy21osti/79761.pdf>. Accessed on 18 June 2026.
- North American Electric Reliability Corporation (NERC). (2017). Integrating inverter-based resources into low short-circuit strength systems. https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/irpwg/item_4a_integrating_inverter-based_resources_into_low_short_circuit_strength_systems_-_2017-11-08-final.pdf. Accessed on 18 June 2026.
- North American Electric Reliability Corporation (NERC). (2023). Quick reference guide: Inverter-based resource activities. https://www.nerc.com/globalassets/initiatives/inverter-based-resource-activities/ibr_quick_reference_guide_activities.pdf. Accessed on 18 June 2026.
- Pohl, E., and McKenna, K. (2024). Interconnection of distributed energy resources in the Indian context: IEEE 1547-2018 adaptation for locally-appropriate grid code development. National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy24osti/87756.pdf>. Accessed on 18 June 2026.
- Rahman, K., Khan, I., and Iqbal, A. (2024). Reviewing control paradigms and emerging trends of grid-forming inverters. *Energies*, *17*(10), 2400. <https://doi.org/10.3390/en17102400>
- Rangarajan, S. S., Collins, E. R., and Fox, J. (2024). Grid forming inverter as an advanced smart inverter to support power systems. *Electricity*, *6*(3), 51.

- Tayyebi, A., Groß, D., Anta, A., Kupzog, F., and Dörfler, F. (2020). Frequency stability of synchronous machines and grid-forming power converters. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 8(2), 1004-1018.
- Tina, G. M., Gagliano, A., and Nocera, F. (2024). The impact of grid-forming vs. grid-following converters on frequency regulation services. *Energies*, 17(23), 5827. <https://doi.org/10.3390/en17235827>
- Xu, Z., Liu, Y., Wang, J., and Zhang, L. (2023). Stability analysis of different control modes of grid-forming converters in renewable-energy systems. *Frontiers in Energy Research*, 11, 1242024. <https://doi.org/10.3389/fenrg.2023.1242024>
- Yu, L., Li, Y., Wang, X., and Liu, F. (2024). Multiple renewable short-circuit ratio for assessing weak grid conditions in power systems with high renewable penetration. *CSEE Journal of Power and Energy Systems*. Advance online publication.
- Zhang, Q., Hu, Q., Sun, S., Mei, D., Liu, S., and Liu, X. (2023). Voltage and frequency instability in large PV systems connected to weak power grid. *Frontiers in Energy Research*, 11, 1210514. <https://doi.org/10.3389/fenrg.2023.1210514>