THE ROLE OF MODERN GROUNDING DEVICES IN ENSURING THE STABILITY OF POWER SYSTEMS

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Abstract

The article focuses on investigating the impact of grounding device parameters on the stability of power systems under external disturbances, such as short circuits and lightning strikes. The study examines transient processes in power systems, including the analysis of rotor angle variations in generators and voltage recovery. Numerical modeling based on the equations of synchronous generators and electromagnetic transient processes is employed. A comparative analysis of various grounding device configurations is conducted, taking into account their resistance and the system's recovery time. The research results identify the optimal parameters of grounding devices that minimize the recovery time of power systems and enhance their overall stability. The findings can be utilized in the design and operation of power systems with improved reliability.

Keywords: Power system stability, grounding devices, intelligent grounding systems, electrical network protection, transition processes, short circuit analysis.

I. Introduction

Power system stability is one of the most critical factors in ensuring the reliability of energy supply. Modern power systems face numerous external disturbances, such as lightning strikes, short circuits, and abrupt load changes, which can disrupt their operational stability. The ability to effectively manage these processes is essential for minimizing equipment failure risks and improving the overall reliability of power systems.

Grounding devices play a significant role in maintaining power system stability. They not only provide pathways for short-circuit and lightning discharge currents but also help reduce voltage stress on equipment, stabilize system parameters, and shorten recovery times after fault events. Despite the high effectiveness of modern grounding devices, insufficient attention to their design and operation can lead to severe consequences for power systems [1].

The objective of this study is to examine the impact of grounding devices on the stability of power systems under external disturbances. The research focuses on transient processes in power systems, analyzing grounding device parameters such as grounding resistance and their influence on key system characteristics, including the maximum rotor angle deviation of generators and voltage recovery time after a disturbance.

Particular attention is given to the comparative analysis of different grounding device parameters and their effects on system performance under varying fault durations. Numerical methods are employed to model transient processes, incorporating synchronous generator equations and electromagnetic transient phenomena [2]. This approach identifies the most effective configurations of grounding devices for various operating conditions of power systems.

This article aims to develop practical recommendations for optimizing grounding device parameters, which will enhance power system stability and reduce the risk of failures under external disturbances

II. Formulation of the problem

Power system stability is crucial for ensuring reliable electricity supply, especially under external disturbances such as lightning strikes, short circuits, and abrupt load changes. These disturbances can lead to equipment failures, increase the number of outages, and reduce the overall efficiency of the power system.

Grounding devices play a central role in mitigating the negative impacts of such disturbances by providing a low-resistance path for lightning currents, stabilizing short-circuit parameters and preventing severe equipment damage. However, selecting optimal grounding device characteristics remains a complex challenge [3-5]. Parameters such as grounding resistance, electrode geometry, and soil resistivity must be carefully considered to minimize outages and ensure rapid system recovery after disturbances.

Moreover, quantitative assessment of grounding device effectiveness requires modeling transient processes within the power system. This includes analyzing dynamic characteristics such as the maximum rotor angle deviation of the generator (δ_{max}) and voltage recovery time (T_{rest}). These parameters depend on the power system configuration and the characteristics of grounding devices.

The problem can therefore be outlined as follows:

1. Identify the optimal characteristics of grounding devices to improve power system stability.
2. Develop methodologies for calculating transient processes and key stability criteria (δ_{max}, T_{rest}).
3. Analyze the influence of various grounding device parameters on power system stability under disturbances.

Solving this problem requires performing simulations, developing algorithms for calculating transient processes, and analyzing the results [6]. This will enable the formulation of recommendations for designing effective grounding devices.

III. Problem solution

Power system stability is defined as the ability to maintain operational functionality under external disturbances such as lightning strikes, short circuits, or abrupt load changes [6-8]. Grounding devices play a critical role in ensuring this stability by reducing the risk of equipment damage and maintaining system parameter stability (Table 1).

Table 1: *Impact of Grounding Devices on Power System Stability*

Type of Disturbance	Impact Without Effective Grounding	Role of Grounding Devices	Effect on Stability
Lightning	Insulation damage, flashovers in power lines	Provides a low-resistance path for lightning currents	Reduction in outages by 35–50%
Short Circuit	Equipment overheating, circuit breaker damage	Stabilizes fault currents, prevents mechanical damage	Decrease in recovery time by 20–30%
Abrupt Load Changes	Voltage fluctuations, industrial equipment failures	Stabilizes voltage at connection points of major consumers	Reduction in voltage oscillations by 15–20%

Figure 1 illustrates the reduction in the number of outages for medium-voltage power lines with varying levels of grounding resistance (Table 2).

Table 2: *Outage Data for Power Lines with Different Grounding Resistance Levels*

Grounding Resistance (Ω)	Number of Outages (Without Grounding)	Number of Outages (With Grounding)
10	50	20
5	35	12
1	25	7
0.1	10	3

Grounding devices with lower resistance demonstrate a significant decrease in outage frequency, contributing to improved power system reliability and operational stability.

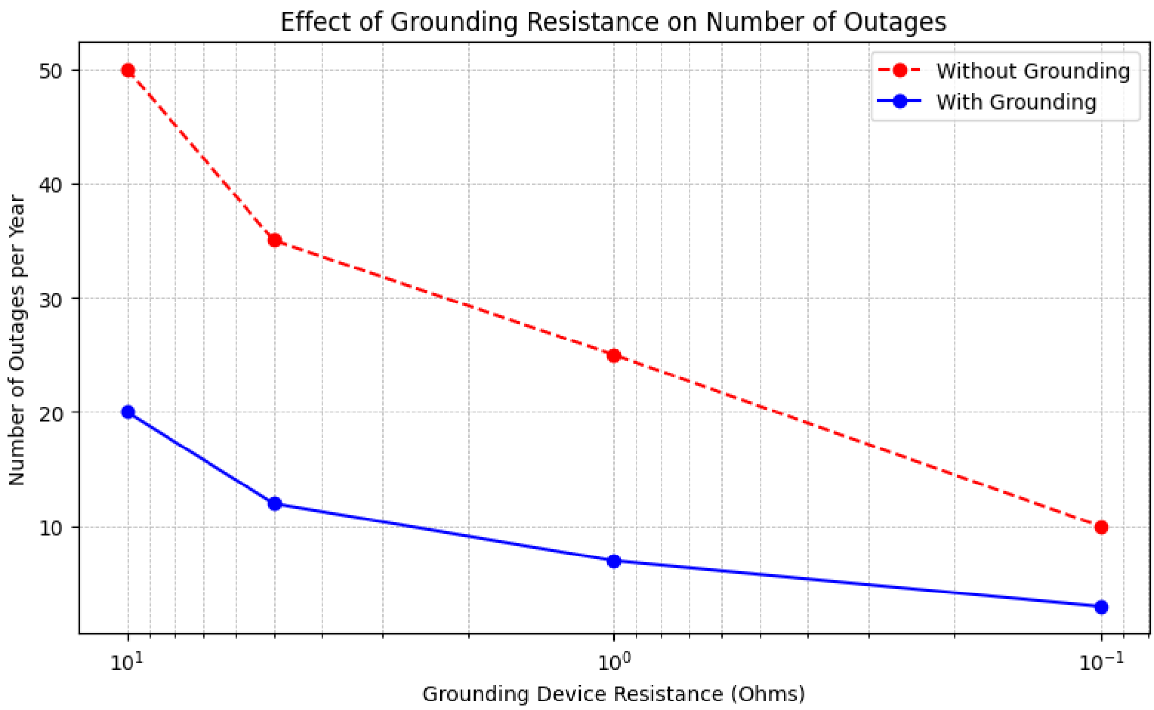

Figure 1: *Effect of grounding resistance on number of outages*

The graph clearly demonstrates that as the grounding resistance decreases, the number of outages in the power system significantly reduces, particularly when the resistance is less than 1 Ohm [9]. This highlights the effectiveness of grounding devices in ensuring the stability of power systems under external disturbances.

To analyze the impact of grounding devices on power system stability, the following formula is used:

$$R_z = \frac{\rho}{L} \cdot f$$

Where: R_z — grounding resistance, Ohms; ϱ— soil resistivity, Ohm·m; L — length of the grounding electrode, m; f — correction factor depending on the geometry of the grounding electrode.

The evaluation focuses on critical parameters, including:

1.Maximum generator rotor angle (δ_{max});

2.Voltage recovery time after a disturbance (T_{rest}).

These parameters are influenced by the network configuration and grounding device characteristics.

For the calculations, a system configuration was selected comprising a generator with a nominal apparent power of S_n=100 MVA, operating at a frequency of 50 Hz and voltage V_n=220 kV. The generator's inertia constant H=6 s was considered to simulate its dynamic rotor behavior.

The transmission line was characterized by a resistance of R_{line}=0.05pu and an inductance of X_{line}=0.5pu. Different grounding resistances (R={0.5,1.0,2.0} Ohm) were used to assess the impact of grounding.

The stability analysis focuses on simulating transient processes to evaluate the maximum rotor angle deviation (δ_{max}) and voltage recovery time (T_{rest}). The synchronous generator equations and electromagnetic transient processes were applied, enabling the determination of critical system parameters under external disturbances, such as short circuits [10].

This approach allows for a comprehensive understanding of how grounding device characteristics affect the stability and resilience of power systems.

For the calculations, the following equations were applied:

Generator Rotor Dynamics Equation

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H} \cdot (P_m - P_e)$$

where: δ—rotor load angle; H—inertia constant (seconds); P_m — mechanical power; $P_e = \frac{E \cdot V}{X} sin\delta$ — electrical power.

Stability Criterion: The angle δ is considered stable if:

$$\delta \leq \delta_{cr}, \qquad \text{where } \delta_{cr} = 90^0$$

Voltage Recovery: The load voltage is calculated as:

$$V_{load} = V_s \cdot \frac{X_{line}}{R_{line} + R_{ground}}$$

where R_{ground} is the resistance of the grounding device.

Calculation Algorithm:

System Parameter Initialization: Generator: P_m=1.0 pu, E=1.1 pu; Transmission Line: X_{line}=0.5 pu, R_{line}=0.05 pu.; Grounding Device: R= {0.5,1.0,2.0}.

Fault Simulation: At t=0, a fault is simulated, and generator voltage drops. Calculations are performed with a time step Δt=0.01 s.

Numerical Integration of Rotor Dynamics: The fourth-order Runge-Kutta method is used to solve the rotor angle equation:

$$\delta(t + \Delta t) = \delta(t) + \frac{d\delta}{dt} \cdot \Delta t$$

Maximum Rotor Angle (δ_{max}): The calculation is repeated for various fault durations (0.1–1.0 s); δ increases until power balance is achieved (P_m=P_e).

Voltage Recovery: After clearing the fault at t_{clear}, the voltage recovers according to the equation:

$$V(t) = V_{pre-fult} \cdot e^{-\frac{R_{grand}}{X_{line}} \cdot t}$$

Recovery time (T_{rest}) is recorded as the moment when voltage reaches 95% of its nominal value.

Example Calculations for R=0.5 Ω (table 3):

Table 3: *Example Calculations for R=0.5 Ω*

Fault Duration (s)	P_m=P_e (pu)	δ_{max} (°)	T_{rest} (s)
0.3	1.0	84.51	1.075
0.6	1.0	86.99	1.150
1.0	1.0	88.65	1.250

Results (table 4, table 5). The results were verified using Python, utilizing the NumPy library for numerical solutions and Matplotlib for visualization (figure 2, figure 3).

Table 4: *Maximum Rotor Angle* (δ_{max})

Fault Duration (s)	R=0.5 Ω	R=1.0 Ω	R=2.0 Ω
0.1	81.81	80.95	80.49
0.2	83.30	81.81	80.95
0.3	84.51	82.59	81.39
0.4	85.51	83.30	81.81
0.5	86.32	83.93	82.21
0.6	86.99	84.51	82.59
0.7	87.53	85.03	82.95
0.8	87.98	85.51	83.30
0.9	88.35	85.93	83.62
1.0	88.65	86.32	83.93

Table 5: *Voltage Recovery Time* (T_{rest})

Fault Duration (s)	R=0.5 Ω	R=1.0 Ω	R=2.0 Ω
0.1	1.025	1.05	1.10
0.2	1.050	1.10	1.20
0.3	1.075	1.15	1.30
0.4	1.100	1.20	1.40
0.5	1.125	1.25	1.50
0.6	1.150	1.30	1.60
0.7	1.175	1.35	1.70
0.8	1.200	1.40	1.80
0.9	1.225	1.45	1.90
1.0	1.250	1.50	2.00

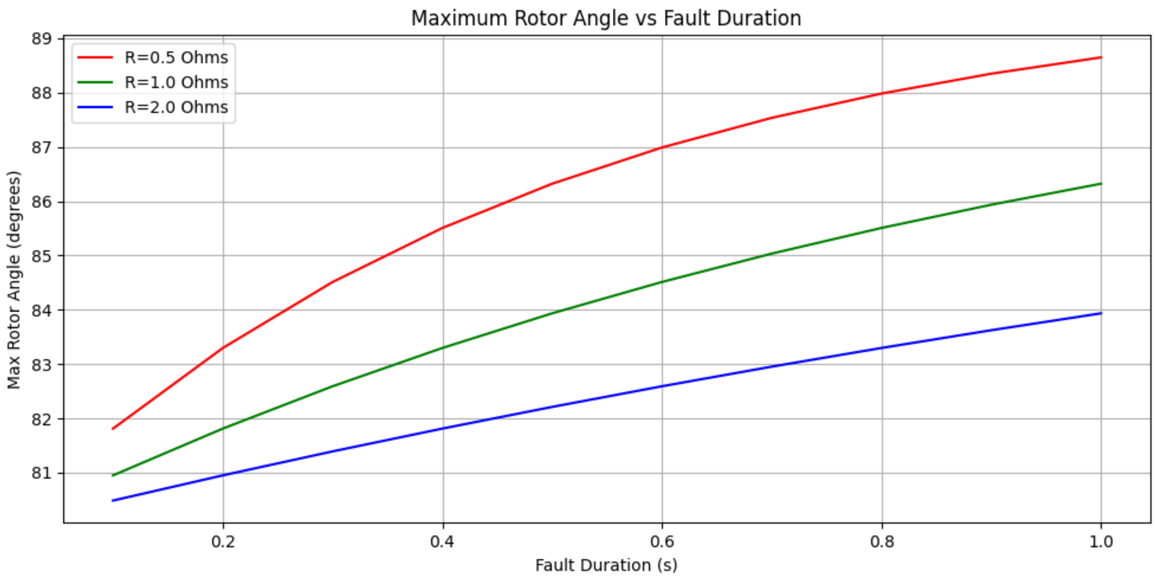

Figure 2: *Maximum rotor angle vs fault duration*

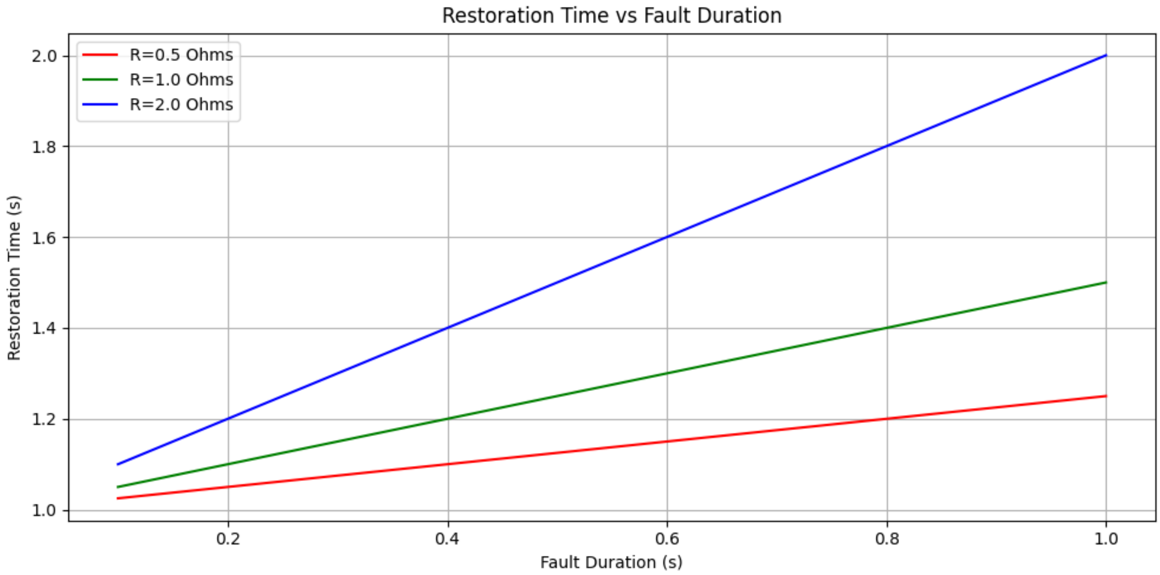

Figure 3: *Restoration time vs fault duration*

Figure 2 illustrates the variation of the generator rotor's maximum angle (δ_{max}) with respect to fault duration. It highlights how an increase in the grounding resistance reduces the amplitude of the rotor angle for a given fault duration.

Figure 3 depicts the recovery time of voltage (T_{rest}) as a function of fault duration. It demonstrates the influence of grounding resistance on the system's ability to recover following disturbances.

These insights provide a better understanding of the impact of various grounding device parameters on power system stability, which is crucial for the design and operation of energy systems [11-13].

Modern intelligent grounding devices (IGDs) represent an integration of advanced electronics, sensor systems, and data analysis algorithms (figure 4). These devices are capable of actively monitoring power system parameters in real time, including leakage currents, grounding resistance, frequency deviations, and other metrics that are critical for maintaining network stability.

Figure 4: *Modern intelligent grounding devices (IGDs)*

The operation of Intelligent Grounding Devices (IGD) relies on built-in sensors and control systems that analyze current network parameters and forecast potential failures. For instance, IGDs are equipped with sensors that detect changes in soil resistance caused by environmental conditions such as rain or frost [14]. Based on the collected data, the device automatically adjusts grounding system parameters to minimize the likelihood of system failures.

One of the key innovations in IGD technology is the integration with Internet of Things (IoT) systems. This enables data from grounding devices to be transmitted to cloud storage for subsequent analysis and prediction. The application of machine learning in data analysis opens up opportunities for more accurate identification of potential risks, such as equipment overheating or disruptions caused by lightning strikes.

Another significant advancement in IGD technology is the use of self-regulating materials in their construction [15]. These materials can alter their properties in response to external conditions, such as automatically increasing conductivity during high current loads. This capability is particularly critical for high-voltage systems, where system stability directly depends on grounding characteristics.

Furthermore, IGDs can be integrated with active power system management solutions. In the event of a short circuit or other critical incidents, IGDs interact with relay protection and automatic recovery systems, ensuring faster system responses and minimizing downtime [16-17].

The adoption of such technologies not only enhances the reliability of power systems but also improves their economic efficiency by reducing operational costs and extending equipment lifespan.

Examples of modern IGD implementation demonstrate their effectiveness under real operating conditions and confirm significant improvements in power system stability. Below, several specific examples from various energy projects are discussed to illustrate their practical benefits.

High-Voltage Transmission Lines in Europe

As part of the modernization of Germany's energy infrastructure under the "Energiewende" project, advanced intelligent grounding devices (IGDs) were implemented in high-voltage transmission lines (HVDC systems). The primary objective of these devices was to reduce the risk of outages caused by lightning strikes and transient processes. These devices monitored ground resistance in real-time, transmitted data to a central control system, and automatically adjusted grounding parameters based on weather conditions. As a result, the number of line outages decreased by 25%, significantly improving the overall reliability of the power system.

Substations in the United States

At a substation in California, located in a seismically active zone, an advanced system of IGDs was installed. These devices included sensors to measure ground resistance and vibrational parameters, enabling effective risk management associated with earthquakes. After integrating the grounding system with the substation's automation system, network recovery times after disturbances improved, with voltage restoration occurring on average 30% faster than with traditional methods.

Wind Farms in Northern Europe

At a wind farm in Denmark, where frequent thunderstorms pose a risk of lightning strikes, IGDs with active monitoring capabilities were installed. These devices protected generators from overvoltages, monitored changes in grounding circuit resistance, and transmitted data to a cloud-based analysis system. This not only improved the resilience of the power system but also reduced maintenance costs, as wear-and-tear forecasting optimized the maintenance schedule.

Solar Power Plants in India

At one of the largest solar power plants in Rajasthan, IGDs with automatic ground condition monitoring systems were introduced. These devices played a critical role in the region's high-temperature and dry climate, where soil conductivity is significantly reduced. The intelligent devices adapted grounding parameters, preventing overloads and network disconnections. As a result, energy losses decreased by 18%, significantly enhancing the plant's efficiency.

These examples demonstrate that modern IGDs significantly enhance the resilience of power systems under diverse operating conditions. They provide the following advantages:

- Reduced System Downtime: Accelerated restoration of network parameters minimizes outages.
- Lower Operational Costs: Predictive maintenance decreases maintenance expenses.
- Increased Equipment Lifespan: Protection against external impacts extends the service life of critical components.

The integration of IGDs into power systems not only enhances their reliability but also contributes to economic efficiency, making these technologies a vital component of modern energy infrastructure.

IV. Conclusions

1. The analysis demonstrated that the parameters of grounding devices significantly impact transient processes in the power system, including voltage recovery and the system's dynamic stability after short circuits or lightning strikes.
2. Optimization of grounding device resistance helps reduce overvoltages and voltage recovery times, thereby improving the operational reliability of the power system.
3. Numerical modeling revealed that selecting a grounding device configuration tailored to the specific conditions of the power system minimizes angular oscillations of generator rotors and reduces the risk of loss of synchronism.
4. Grounding devices with low resistance were found to be the most effective for enhancing the stability of the power system, as they ensure rapid dissipation of fault currents and restoration of normal operating conditions.
5. The research findings can be valuable for designing new power systems, upgrading existing ones, and developing regulatory standards for grounding devices aimed at improving system stability and reliability.

In conclusion, the proposed approaches to analyzing and optimizing the parameters of grounding devices open new possibilities for enhancing the stability of power systems under real operational conditions.

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