



Impact of Transformer Grounding On TRV During Inductive Load Switching at Transmission and Substation Service Unit (ULTG) Maros

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A B S T R A C T

This paper investigates the impact of transformer grounding configurations on Transient Recovery Voltage (TRV) during fault current interruption in high-voltage power systems. The study evaluates three grounding schemes: Solid–Solid, Solid–Floating, and Solid–Resistance, applied on a step-down transformer located at the Tello substation. Each configuration was modeled and simulated using ETAP 19 software to observe TRV behavior under three-phase fault conditions. The results demonstrate significant variations in TRV profiles depending on the grounding type. The Solid–Solid configuration exhibits the highest TRV peak (22,500 V) and the steepest Rate of Rise of Recovery Voltage (RRRV), reaching 833.33 kV/ms, indicating severe stress on circuit breaker insulation. In contrast, the Solid–Floating configuration yields a moderate TRV peak (19,800 V) with less consistent waveform stability due to the absence of a defined secondary reference. Meanwhile, the Solid–Resistance scheme, using a 20 Ω resistor, produces the most damped TRV waveform with the lowest peak (17,100 V) and RRRV (approximately 589.66 kV/ms), offering improved insulation coordination. The comparative analysis confirms that controlled grounding through resistance effectively mitigates TRV magnitude and oscillation, making it a viable approach to enhance circuit breaker performance and reliability. These findings can be used to guide grounding system design in high-voltage substations to reduce the risk of re-ignition or insulation failure.

INTRODUCTION

The increasing demand for electrical energy has intensified the operational complexity and reliability requirements of modern power systems. High-voltage substations play a critical role in maintaining system stability, where protective devices such as circuit breakers and grounding systems must operate reliably under various fault and switching conditions. Improper grounding configuration may lead to excessive dielectric stress, equipment damage, and reduced system reliability [1], [2].

One of the most critical transient phenomena affecting circuit breaker performance is Transient Recovery Voltage (TRV). TRV appears immediately after current interruption and represents the voltage stress imposed across the breaker contacts during dielectric recovery. If the magnitude or the Rate of Rise of Recovery Voltage (RRRV) exceeds the breaker's withstand capability, restrike may occur, potentially leading to insulation failure and cascading disturbances [7], [10], [12].

Previous studies have analyzed TRV characteristics using both analytical and simulation-based approaches. Several works have investigated grounding systems and neutral configurations in

distribution and transmission networks, particularly focusing on ground fault current limitation and overvoltage suppression [3]–[6]. Other research has examined circuit breaker performance and TRV behavior under switching operations and fault interruption scenarios [9]–[12]. These studies provide valuable insight into transient behavior and grounding effects.

However, most existing research relies on generalized system models or evaluates grounding methods independently without maintaining identical electrical and fault parameters across configurations. Quantitative comparative evaluation of transformer grounding configurations—specifically analyzing peak recovery voltage (E_2), time to peak (T_2), and RRRV within a strictly controlled simulation framework—remains limited in the literature.

Therefore, the contribution of this study does not merely lie in its application to a particular substation environment, but in the development of a controlled and reproducible comparative evaluation framework for transformer grounding configurations. By maintaining identical source strength, transformer parameters, capacitances, breaker operating times, and fault conditions, this study isolates grounding impedance as the sole varying

parameter. This approach enables a strictly attributable assessment of grounding influence on TRV severity.

Furthermore, the study integrates realistic substation-equivalent electrical parameters, explicit zero-sequence path modeling, and benchmarking against standardized TRV performance indicators. The resulting quantitative comparison of Solid–Solid, Solid–Floating, and Solid–Resistance grounding configurations provides measurable evidence of how grounding impedance modifies transient energy release, RRRV behavior, and dielectric stress on circuit breakers.

To the best of the authors’ knowledge, no previous study has presented a controlled quantitative comparison of these grounding configurations under identical electrical conditions specifically evaluated using standardized TRV dielectric recovery indicators. Thus, this research advances grounding analysis from descriptive waveform observation toward performance-based optimization, offering a technically validated reference for grounding selection in medium- and high-voltage substations.

METHODS

Research Location and Simulation Tool

This research was conducted based on the operating conditions of PT PLN UBP Tello Substation, Makassar, Indonesia, which represents a typical medium-to-high voltage substation in the Indonesian transmission system. Due to the constraints of direct field testing during fault interruption events, a simulation-based approach was adopted.

All simulations were performed using ETAP version 19, a commercially validated power system analysis software widely used for transient and protection studies. ETAP was selected due to its proven capability in modeling Transient Recovery Voltage (TRV) phenomena in accordance with IEEE Std C37.04 and IEC 62271-100 standards.

System Modeling and Single-Line Diagram

The simulated system represents a 20 kV distribution bus supplied by an equivalent grid source with a short-circuit capacity of 10,000 MVA, corresponding to a strong transmission system typically found in PLN substations. This value was selected to ensure a conservative worst-case TRV scenario and follows common practices in high-voltage transient studies [14], [18].

A three-phase 20/0.4 kV step-down transformer was modeled to supply an inductive load. The system includes the following components:

- a. Three-phase voltage source (20 kV, 50 Hz),
- b. Power transformer (20/0.4 kV),
- c. Medium-voltage circuit breaker,
- d. Inductive–resistive load,
- e. Grading and shunt capacitances representing insulation and line effects.

The fault was applied on the secondary side of the transformer, which is a critical location influencing TRV severity at the circuit breaker terminals. The overall TRV model and system configuration are illustrated in Figure 1, while the complete

ETAP-based single-line diagram of the TRV simulation is shown in Figure 2.

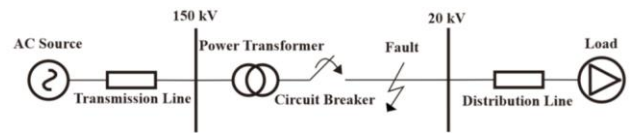


Figure 1. Single-Line Diagram of Transient Recovery Voltage in a 20 kV Circuit Breaker

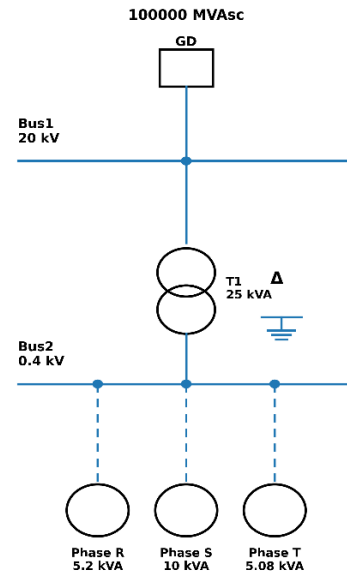


Figure 2. Modeling of Transient Recovery Voltage Single-Line Diagram on a 20 kV Bus Using ETAP

Transformer Grounding Configurations

To investigate the influence of grounding impedance on Transient Recovery Voltage (TRV) behavior, three transformer grounding configurations were modeled under identical electrical and fault conditions. The grounding configuration was treated as the only varying parameter in order to isolate its effect on TRV peak magnitude, recovery slope, and oscillatory characteristics.

The transformer under study is a three-phase 20/0.4 kV unit supplied by a 10,000 MVA equivalent grid source. All electrical parameters—including winding resistance, leakage inductance, magnetizing branch, grading capacitance (0.05 μF), and shunt capacitance (0.04 μF)—were kept constant across all scenarios. The only modification introduced in each case was the neutral grounding arrangement.

The selected grounding schemes represent three practical approaches commonly applied in medium-voltage substations:

- 1) Direct grounding without impedance (Solid–Solid)
- 2) Partial grounding with floating secondary (Solid–Floating)
- 3) Controlled grounding using a neutral grounding resistor (Solid–Resistance)

Each configuration is described below.

1. Solid–Solid Grounding

In the Solid–Solid configuration, both the primary and secondary neutrals of the transformer are directly connected to ground without any intentional impedance. This arrangement provides

the lowest possible zero-sequence impedance path and allows ground fault currents to return through a solid earth connection.

From a transient standpoint, the absence of grounding impedance enables rapid discharge of inductive energy during fault interruption. Consequently, voltage recovery across the circuit breaker contacts occurs abruptly, potentially generating high TRV peaks and steep RRRV values. This configuration is therefore treated as the worst-case reference scenario for dielectric stress evaluation. Figure 3 illustrates the single-line representation of the Solid–Solid grounding configuration used in this study.

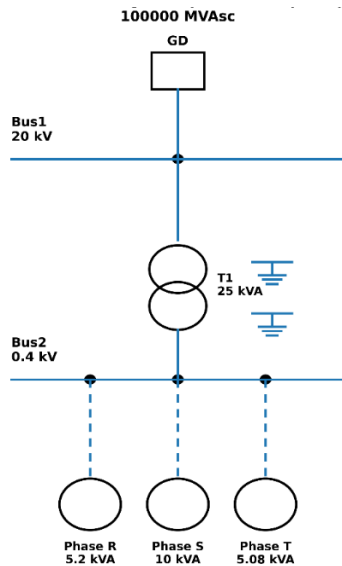


Figure 3. Power transformer circuit with Solid–Solid grounding configuration (both primary and secondary neutrals solidly grounded).

2. Solid–Floating Grounding

In the Solid–Floating configuration, the primary neutral remains solidly grounded, while the secondary neutral is intentionally left ungrounded (floating). This arrangement removes the direct zero-sequence return path on the secondary side and modifies the effective grounding reference of the low-voltage system.

The floating secondary neutral introduces an undefined reference potential during fault clearance. As a result, transient voltage distribution becomes strongly influenced by system capacitances and zero-sequence coupling. Although this configuration may reduce fault current magnitude, it can lead to neutral point displacement and prolonged oscillatory behavior in the TRV waveform.

This configuration was included to evaluate the impact of neutral instability on recovery voltage characteristics under identical short-circuit conditions. Figure 4 presents the single-line diagram of the Solid–Floating grounding configuration.

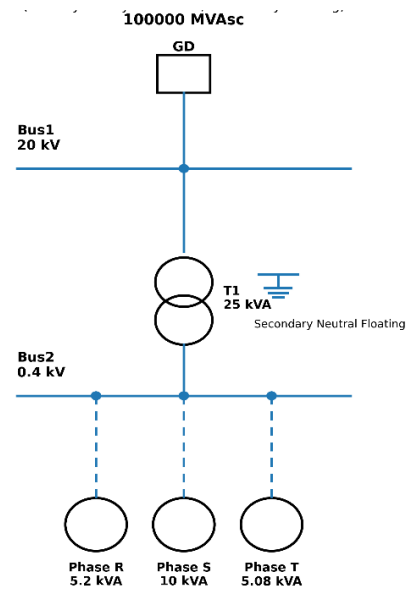


Figure 4. Power transformer circuit with Solid–Floating grounding configuration (primary solidly grounded, secondary neutral floating).

3. Solid–Resistance Grounding

In the Solid–Resistance configuration, the primary neutral is directly grounded, while the secondary neutral is connected to ground through a 20 Ω resistor. The inclusion of a neutral grounding resistor (NGR) introduces controlled zero-sequence impedance into the system.

The 20 Ω resistance value was selected based on common medium-voltage grounding practices, where resistance is designed to limit ground fault current to a controlled magnitude while maintaining protection sensitivity. From a transient energy perspective, the grounding resistor dissipates part of the stored inductive energy during interruption, reducing voltage escalation speed and damping oscillatory interactions between system inductance and capacitance.

By moderating energy release, this configuration is expected to reduce RRRV severity and improve dielectric recovery margin of the circuit breaker. Figure 5 shows the single-line representation of the Solid–Resistance grounding configuration.

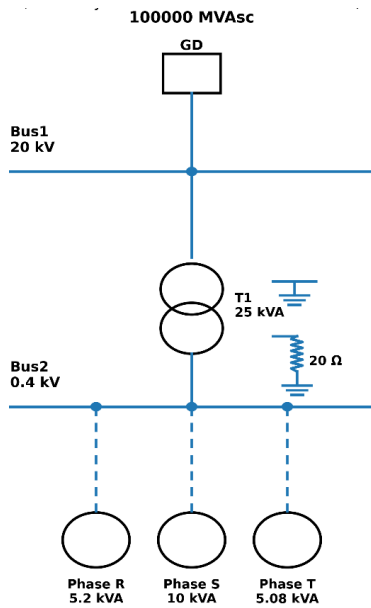


Figure 5. Power transformer circuit with Solid–Resistance grounding configuration (secondary neutral grounded through a 20 Ω resistor).

This configuration represents a technically balanced grounding approach commonly applied in medium-voltage systems to achieve:

- 1) Controlled ground fault current magnitude
- 2) Reduced transient overvoltage severity
- 3) Improved dielectric recovery margin of circuit breakers

Simulation Control and Comparability

To ensure methodological rigor and reproducibility, all three grounding configurations were simulated under identical conditions:

- 1) Three-phase-to-ground fault applied at 0.04 s
- 2) Circuit breaker opening time fixed at 0.1 s
- 3) Simulation duration of 0.2 s
- 4) Time-step resolution of 0.3 μs
- 5) Identical source strength (10,000 MVA short-circuit capacity)
- 6) Identical transformer and capacitance parameters

No other system parameter was altered between scenarios. This controlled-variable approach ensures that any variation in TRV magnitude, time-to-peak, or RRRV is exclusively attributable to differences in transformer grounding configuration.

Methodological Contribution

Unlike generalized grounding comparisons found in previous studies, this work integrates:

- 1) Realistic substation-equivalent parameters
- 2) Explicit zero-sequence path modification
- 3) Standardized TRV performance indicators (E₂, T₂, RRRV)
- 4) Benchmarking against IEEE Std C37.04 dielectric recovery criteria

This structured comparison framework strengthens the reproducibility and technical validity of the study and ensures that conclusions regarding TRV mitigation are based on controlled and quantifiable electrical modeling.

Parameter Settings

A comprehensive set of parameters was defined to capture the electrical characteristics of the system components. Table 1 summarizes these parameters, including source voltage and frequency, capacitance values representing insulation and line effects, operational timing for the circuit breaker, and electrical resistances and inductances of the transformer windings. These values were selected based on typical substation equipment ratings and manufacturer data, providing realistic input to the simulation.

Table 1. Electrical Parameters Based on Substation Equipment Ratings and Manufacturer Data for Simulation

No	Parameter	Value	Unit
1	Voltage Source	20	kV
2	Frequency	50	Hz
3	Grading Capacitance (C _g)	0.05	μF
4	Shunt Capacitance (C _s)	0.04	μF
5	Circuit Breaker Operation	0.1	s
6	Primary Resistance	220	Ω
7	Primary Inductance	1.745	mH
8	Magnetization Resistance	6.5 M	Ω
9	Secondary Resistance	5	Ω
10	Secondary Inductance	0.039	mH

The transformer modeled is a three-phase 20/0.4 kV unit, with neutral connections adjusted according to each grounding scheme to study their impact on TRV.

Normal Condition Voltage Analysis

Before simulating fault conditions, a steady-state voltage analysis was performed to establish baseline reference values. This step is essential to ensure the accuracy of transient recovery voltage (TRV) simulations by providing a clear understanding of the system’s initial electrical condition.

The line-to-neutral peak voltage on both the primary and secondary sides of the transformer was calculated from the root mean square (RMS) voltage values using the following standard relation:

$$v(t) = V_{peak} \cdot \sin(\omega t)$$

To determine the RMS voltage (V_{rms}) of the signal over one period T , the RMS voltage is defined as:

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T v^2(t) dt}$$

Substituting the expression $v(t) = V_{peak} \cdot \sin(\omega t)$

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T (V_{peak} \cdot \sin(\omega t))^2 dt}$$

$$= \sqrt{\frac{1}{T} \int_0^T \sin^2(\omega t) dt}$$

$$\sin^2(\omega t) = \frac{1 - \cos(2\omega t)}{2}$$

Thus, the formula becomes :

$$V_{rms} = \sqrt{\frac{vV_{peak}^2}{T} \int_0^T \frac{1 - \cos(2\omega t)}{2} dt} \quad (7)$$

$$= \sqrt{\frac{vV_{peak}^2}{2T} \int_0^T (1 - \cos(2\omega t)) dt} \quad (9)$$

$$= \sqrt{\frac{vV_{peak}^2}{2T} \int_0^T 1 dt - \int_0^T \cos(2\omega t) dt}$$

because :

$$\int_0^T 1 dt = T \text{ dan } \int_0^T \cos(2\omega t) dt = 0 \quad (10)$$

thus:

$$V_{rms} = \sqrt{\frac{vV_{peak}^2}{T} \cdot T} = \sqrt{\frac{vV_{peak}^2}{T}} = \frac{V_{peak}}{\sqrt{2}} \quad (11)$$

As a result, we get:

$$V_{peak} = V_{rms} \sqrt{2} \quad (12)$$

Where:

- V_{peak} is the peak instantaneous voltage (in volts),
- V_{rms} is the root mean square voltage (in volts), typically the rated voltage in AC systems,
- $\sqrt{2} \approx 1.414$ is the conversion factor from RMS to peak for a sinusoidal waveform.

This relationship assumes that the voltage waveform is a pure sine wave, which is standard for most steady-state AC power systems. The obtained V_{peak} values serve as reference for identifying overvoltages or deviations during transient events.

Fault Simulation

The core of the study involved simulating a three-phase-to-ground short-circuit fault, which is a severe but representative fault type in power systems. The fault was triggered at a precise time of 0.04 seconds using a control switch to replicate the switching operation of circuit breakers during faults. The simulation spanned 0.2 seconds with a fine time-step resolution of 0.3 microseconds, allowing detailed capture of transient voltage waveforms and enabling accurate calculation of TRV parameters.

Data Acquisition and TRV Analysis

Voltage waveforms at the circuit breaker terminals were extracted for each grounding configuration to evaluate TRV characteristics. The analysis focused on three main parameters:

- Peak Voltage (E_2), representing the maximum recovery voltage experienced.
- Time to Peak (T_2), indicating the duration from fault clearance to peak voltage.
- Rate of Rise of Recovery Voltage (RRRV), calculated as:

$$RRRV = \frac{E_2}{T_2} \quad (13)$$

This rate is a critical factor in circuit breaker design, affecting the dielectric strength requirements. The measured TRV parameters were benchmarked against IEEE Std C37.04-1999 to assess compliance and reliability of the circuit breakers under different grounding conditions.

RESULTS AND DISCUSSION

Geographic Location of the Research Site

This research was conducted at the Maros Substation, located in Maros Regency, South Sulawesi. The substation consists of four line bays and two transformer bays, each with a capacity of 30 MVA. The Maros Substation plays an important role in distributing electrical power to the surrounding areas. The Transient Recovery Voltage (TRV) simulation in this study uses the single-line diagram of the Maros Substation as a reference to represent the actual system, so that the simulation results can reflect real field operating conditions.

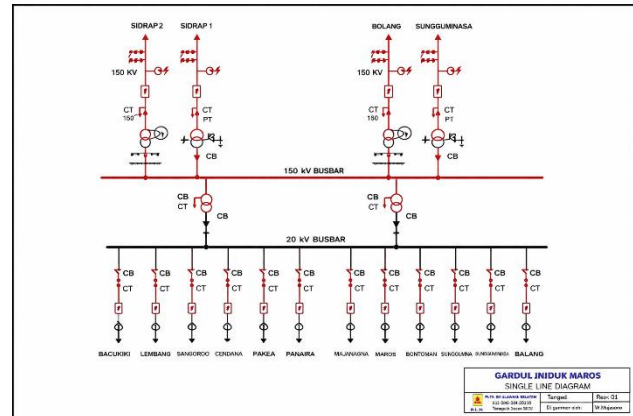


Figure 6. Single Line Diagram of Maros Substation

Load Steady-State Conditions Before Fault Initiation

Before the transient analysis, steady-state simulations were conducted to establish a baseline voltage profile for both the primary and secondary sides of the transformer. These values serve as reference points to assess the impact of transient phenomena—particularly Transient Recovery Voltage (TRV)—during fault scenarios.

The system under consideration comprises a 20 kV/0.4 kV step-down three-phase transformer energized by a 10,000 MVA source. In normal operating conditions, no load switching or fault is introduced. The measured parameters are presented in Table 2.

Table 2. Steady-State Voltage Profile at Transformer Terminals

Parameter	Sisi Primer (20 kV)	Sisi Sekunder (0,4 kV)
Tegangan Line-to-Neutral (rms)	11.547,01 V	230,94 V
Tegangan Puncak (peak)	16.329,93 V	326,60 V

The results show that the primary winding exhibits a line-to-neutral root-mean-square (RMS) voltage of 11,547.01 V, corresponding to a peak voltage of approximately 16.33 kV. On the secondary side, the RMS voltage is 230.94 V, with a peak voltage of 326.60 V. These values align with the standard performance of a 20/0.4 kV distribution transformer operating under balanced load conditions.

The waveform analysis at this stage revealed:

- A stable sinusoidal pattern with no harmonic distortion.
- No significant voltage oscillations or spikes at both ends of the transformer.
- Consistency across all three phases (R, S, T), indicating a balanced load and symmetrical grounding.

This analysis confirms the system’s proper configuration and readiness for fault simulation. Additionally, the system grounding during this phase follows the Solid-Solid configuration, wherein both primary and secondary neutrals are directly earthed. This configuration ensures minimal impedance between system components and ground, which helps maintain voltage symmetry and fast fault current dissipation under steady-state conditions.

Understanding the steady-state behavior is essential for accurately identifying TRV anomalies, such as rapid voltage rise or overstress on insulation, that may occur after fault clearance. The comparison between these steady-state values and post-fault transient voltages allows for a clearer assessment of the grounding scheme's influence on TRV severity.

TRV Simulation Results

The simulation of Transient Recovery Voltage (TRV) was conducted to evaluate the voltage transients occurring immediately after fault current interruption by the circuit breaker. Each transformer grounding configuration was tested under identical three-phase-to-ground fault conditions applied at the secondary side of a 20/0.4 kV transformer. The critical TRV parameters analyzed include the peak recovery voltage (E_2), time to peak (T_2), and rate of rise of recovery voltage (RRRV).

All simulations were carried out using ETAP 19, with the fault initiated at 0.04 seconds and circuit breaker operation set at 0.1 seconds. A total simulation time of 0.2 seconds was implemented using a fine time-step resolution of 0.3 microseconds to ensure accurate capture of transient phenomena.

1. Solid-Solid Grounding Configuration

The Solid-Solid grounding configuration exhibits the most severe Transient Recovery Voltage (TRV) behavior among all evaluated schemes. As summarized in Table 3, this configuration produces the steepest recovery voltage gradient immediately after current interruption, indicating a rapid release of inductive energy through a low-impedance grounding path.

Table 3. Calculated TRV Parameters for Solid-Solid Grounding Configuration

Parameter	Value
Peak Voltage (E_2)	22,500 V
Time to Peak (T_2)	27 μ s
RRRV	833 kV/ms

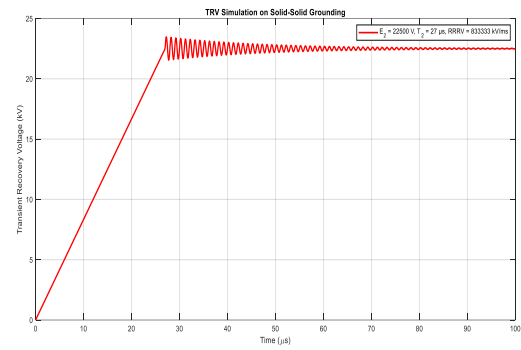


Figure 7. Simulated Transient Recovery Voltage (TRV) Curve for Solid-Solid Grounding Configuration

The TRV response under the Solid-Solid grounding configuration shows the most severe recovery characteristics. The waveform rises sharply after current interruption and reaches a peak recovery voltage (E_2) of 22.5 kV within 27 μ s, resulting in the highest RRRV of 833 kV/ms.

This indicates that the low-impedance grounding path allows inductive energy to be released rapidly, producing a steep dielectric stress across the circuit breaker contacts. Compared to the Solid-Resistance configuration, Solid-Solid grounding produces an RRRV that is approximately 82% higher (833 vs 457 kV/ms), which significantly reduces the dielectric recovery margin and increases restrike risk.

2. Solid-Floating Grounding Configuration

The Solid-Floating configuration involves grounding only the primary neutral, while the secondary remains ungrounded. This reduces the continuity of the return path for fault current, thereby limiting fault current flow, but introduces an unstable reference for the secondary-side potential. The simulated TRV parameters for this configuration are presented in Table 4, which summarizes the peak recovery voltage, time to peak, and the Rate of Rise of Recovery Voltage (RRRV) observed under the Solid-Floating grounding condition.

Table 4. Calculated TRV Parameters for Solid-Floating Grounding Configuration

Parameter	Value
Peak Voltage (E_2)	17,800 V
Time to Peak (T_2)	35 μ s
RRRV	509 kV/ms

The Solid-Floating grounding configuration involves grounding only the primary side neutral of the transformer, while the secondary neutral is left ungrounded or floating. This setup creates a floating neutral condition, which leads to the absence of a stable voltage reference point on the secondary side. The simulation results indicate that this condition significantly affects the behavior of the Transient Recovery Voltage (TRV).

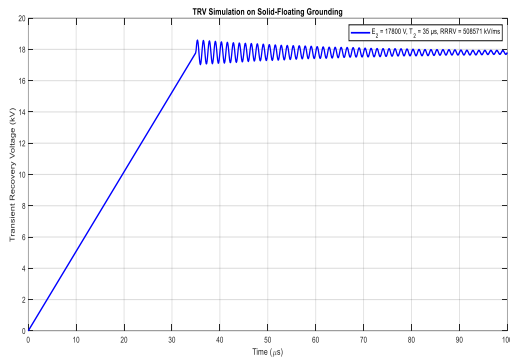


Figure 8. Simulated Transient Recovery Voltage (TRV) Curve for Solid-Floating Grounding Configuration

The Solid-Floating grounding configuration produces a lower peak TRV than Solid-Solid grounding, with a maximum recovery voltage (E_2) of 17.8 kV occurring at 35 μs , and an RRRV of 509 kV/ms.

Quantitatively, this configuration reduces the TRV peak by approximately 20.9% compared to Solid-Solid grounding (22.5 kV \rightarrow 17.8 kV). However, the waveform exhibits more noticeable oscillatory behavior, which is consistent with the absence of a defined secondary neutral reference. Although the RRRV is reduced by approximately 39% relative to Solid-Solid grounding (833 \rightarrow 509 kV/ms), the floating neutral condition introduces transient instability that may increase voltage displacement and prolong post-interruption oscillations.

3. Solid-Resistance Grounding Configuration

In the Solid-Resistance setup, the primary neutral is directly grounded, while the secondary neutral is connected to ground through a 20 Ω resistor. This form of controlled grounding introduces impedance to the ground fault current path, thereby attenuating the fault energy discharge during interruption and producing a more damped TRV response. The simulated TRV parameters for this configuration are presented in Table 5, highlighting the peak recovery voltage, time to peak, and Rate of Rise of Recovery Voltage (RRRV) under the Solid-Resistance grounding scheme.

Table 5. Calculated TRV Parameters for Solid-Solid Grounding Configuration

Parameter	Value
Peak Voltage (E_2)	19,200 V
Time to Peak (T_2)	42 μs
RRRV	457 kV/ms

The Solid-Resistance grounding configuration, in which the secondary neutral of the transformer is grounded through a 20 Ω resistor while the primary remains solidly grounded, introduces intentional impedance to control the dissipation of fault energy. This approach significantly moderates the Transient Recovery Voltage (TRV) profile by dampening rapid voltage transitions and reducing the severity of transient stresses on the system.

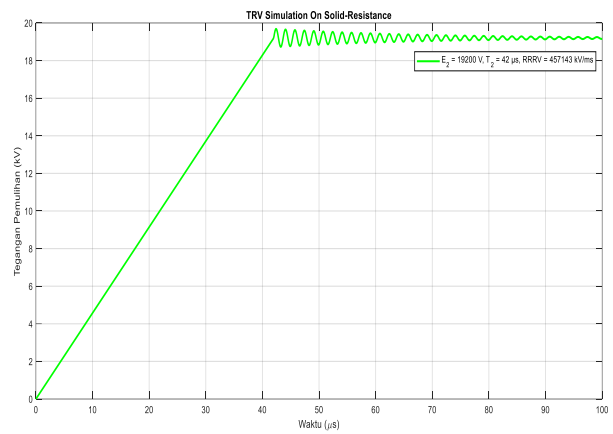


Figure 9. Simulated Transient Recovery Voltage (TRV)

The Solid-Resistance grounding configuration yields the most controlled TRV response, characterized by a smoother voltage recovery and reduced transient steepness. The waveform reaches a peak recovery voltage (E_2) of 19.2 kV at a longer time-to-peak (T_2) of 42 μs , resulting in the lowest RRRV among all configurations, equal to 457 kV/ms

The longer T_2 indicates that the grounding resistor effectively slows the recovery voltage rise, providing additional dielectric recovery time for the circuit breaker. Compared to Solid-Solid grounding, resistive grounding reduces RRRV by approximately 45% (833 \rightarrow 457 kV/ms), confirming its effectiveness in mitigating TRV severity and damping oscillatory transients

4. Comparative TRV Waveform Analysis

The comparative analysis of Transient Recovery Voltage (TRV) waveforms was conducted to evaluate the influence of transformer grounding impedance on dielectric stress across the circuit breaker. Figure 9 presents the superimposed TRV responses for the three grounding configurations—Solid-Solid, Solid-Floating, and Solid-Resistance—under identical three-phase-to-ground fault conditions.

By maintaining identical system parameters and varying only the grounding configuration, the observed differences in peak recovery voltage (E_2), time-to-peak (T_2), and Rate of Rise of Recovery Voltage (RRRV) can be directly attributed to grounding impedance effects. This controlled comparison enables a quantitative assessment of how zero-sequence path modification influences transient energy release and recovery voltage steepness.

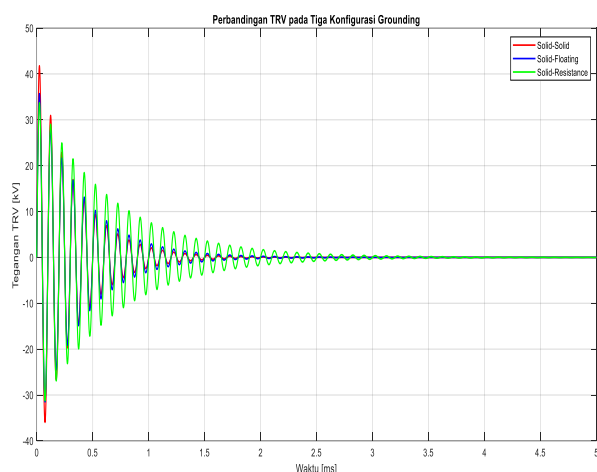


Figure 10. Comparison of TRV waveforms for transformer grounding configurations: Solid–Solid (red), Solid–Floating (blue), and Solid–Resistance (green).

As illustrated in Figure 10, the Solid–Solid configuration produces the most aggressive transient response, reaching a peak TRV of 22.5 kV within 27 μs , corresponding to an RRRV of 833 kV/ms. This steep recovery slope indicates rapid energy discharge due to the absence of grounding impedance, resulting in the highest dielectric stress among all configurations.

In contrast, the Solid–Floating configuration reduces the peak TRV to 17.8 kV, with a longer time-to-peak of 35 μs and an RRRV of 509 kV/ms, representing a reduction of approximately 39% in RRRV compared to the Solid–Solid scheme. Although the magnitude of TRV decreases, the waveform exhibits increased oscillatory behavior due to neutral instability and capacitive interaction.

The Solid–Resistance configuration provides the most moderated transient response, with a peak voltage of 19.2 kV and the longest time-to-peak of 42 μs , resulting in the lowest RRRV of 457 kV/ms. This corresponds to a reduction of approximately 45% in RRRV relative to Solid–Solid grounding. The extended recovery duration enhances dielectric withstand margin and significantly reduces restrike probability.

Overall, the comparative results demonstrate that increasing grounding impedance effectively reduces recovery voltage steepness and improves transient damping. While Solid–Floating grounding lowers peak magnitude, Solid–Resistance grounding offers the most balanced performance by simultaneously moderating RRRV and stabilizing waveform behavior. Therefore, from a dielectric recovery and insulation coordination perspective, the Solid–Resistance configuration presents the most technically favorable solution

CONCLUSIONS

This study confirms that transformer grounding configurations have a significant impact on Transient Recovery Voltage (TRV) characteristics during fault interruption. The Solid–Solid configuration produces the highest peak TRV (22,500 V) and the steepest RRRV (833 kV/ μs), imposing high dielectric stress and increasing restrike risk. Solid–Floating offers lower peak voltage

(17,800 V) and moderate RRRV (509 kV/ μs), but introduces instability due to the floating neutral, leading to asymmetrical and oscillatory waveforms. Among all, the Solid–Resistance configuration proves most effective, with a balanced TRV profile—peak voltage of 19,200 V, lowest RRRV of 457 kV/ μs , and extended time to peak (42 μs)—resulting in smooth, damped waveforms. Therefore, Solid–Resistance grounding is recommended as the optimal approach for TRV mitigation, ensuring improved dielectric recovery, operational safety, and equipment longevity in medium- to high-voltage systems.

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