

Transient Recovery Voltage Analysis of a 500-kV Transmission Line with Additional Series Reactors

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Abstract — This study investigates the impact of series reactor installation on transient recovery voltage (TRV) and the rate of rise of recovery voltage (RRRV) in the 500 kV Suralaya–Suralaya Baru transmission line within the projected 2030 Java–Madura–Bali (JAMALI) power system. Using data from the PLN RUPTL 2021–2030 [21], the research evaluates how series reactors influence TRV and RRRV during a single line-to-ground or short-line fault occurring 5% from the Suralaya line. Simulations were conducted in DlgSILENT PowerFactory using detailed transmission line modeling that incorporates line coupling and stray capacitance, with model validation performed through power flow and short-circuit comparisons. Two scenarios, before and after the installation of series reactors, were assessed. Prior to installation, TRV was 872.9 kV and RRRV was 2.14 kV/μs, while after installation TRV increased to 922.2 kV and RRRV increased to 11.9 kV/μs. Although the TRV remains within IEEE Std C37.011–2019 limits [11], the RRRV exceeds the standard threshold, indicating the need for mitigation. The study's novelty lies in developing a detailed Java–Madura–Bali system model in PowerFactory and applying network reduction to improve simulation efficiency. As the effects of series reactors on TRV and RRRV in this system have not been previously examined, the findings provide essential insights for ensuring circuit breaker reliability and supporting future high-voltage system planning.

Keywords: Circuit breaker, Series reactor, Transmission line, Transient recovery voltage.



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INTRODUCTION

The expansion of generation and transmission infrastructure projected in Indonesia's RUPTL PT PLN (Persero) 2021–2030 [21] has intensified short-circuit current levels in large interconnected grids such as Java–Madura–Bali (JAMALI), raising the risk of exceeding equipment short-circuit withstand ratings and threatening operational reliability; limiting fault current with series reactors is a practical mitigation, yet the added inductance can adversely affect circuit-breaker transient recovery voltage (TRV) and the rate of rise of recovery voltage (RRRV), with potential insulation-coordination consequences. The application of series reactors limit fault current while altering TRV across 500 kV breakers [6], the TRV analysis on 110 kV and 220 kV SF₆ circuit breakers using short-circuit fault simulations in EMTP-RV shows

that the distance between the circuit breaker and the fault point affects the maximum rate of rise of TRV [12], and installing series reactors tends to raise TRV peaks in transmission systems [28]. The TRV becomes excessively high when the simulation is performed without optimization using all parameters from reference, which in turn causes the RRRV to exceed the IEC 62271-100 T75 standard [27]. Inductive FCLs often result in the main circuit breaker experiencing an excessively high RRRV during operation [23]. The HCSR-based FCL with fast switches effectively limits fault current, but it can increase the circuit breaker's RRRV due to its inherent inductance and capacitance. The relationship between FCL inductance and RRRV is nonlinear, and the RRRV reaches its peak when the FCL inductance approaches the system's equivalent inductance [22].

Despite these findings, there is limited, system-specific evidence for the planned 500 kV Suralaya–Suralaya Baru line (JAMALI 2030) under single line-to-ground short-line fault (SLF) conditions, with realistic modeling of stray capacitance and explicit benchmarking against IEEE Std C37.011-2019 limits, this paper occupies that research gap by providing a focused TRV/RRRV assessment tied to an operational planning case. We aim to quantify how series reactor installation affects TRV and RRRV on the Suralaya–Suralaya Baru 500 kV transmission line using DiGSILENT PowerFactory 2021 (with DPL) for EMT simulation and Python for waveform processing. Installing series reactors on the target line will maintain TRV within IEEE Std C37.011-2019 SLF envelopes but may drive RRRV above standard thresholds. Simulations indicate a peak TRV of 922.2 kV (within IEEE Std C37.011-2019) and an RRRV of 11.9 kV/μs (exceeding the standard).

METHOD

In this study, the object of analysis is the 500 kV Suralaya–Suralaya Baru transmission line as stated in the PLN RUPTL 2030. This transmission line is part of the Java–Madura–Bali power system, has a length of 1.325 km, and is classified as a short transmission line. The research begins with a literature review related to transient recovery voltage (TRV), followed by data collection for the Java–Madura–Bali system based on the PLN RUPTL 2021–2030. The 2030 Java–Madura–Bali power system is then modeled using the DiGSILENT PowerFactory 2021 software, and a load flow analysis is conducted to ensure that the model and simulations operate correctly. The next stage includes the network reduction process and modeling of the Suralaya–Suralaya Baru system by considering line coupling effects and stray capacitance calculations. The developed model is validated through a comparison of short-circuit values before and after network reduction. Subsequently, TRV simulations are carried out for conditions before and after the installation of series reactors, with a single-phase-to-ground fault applied at a distance of 5% from the Suralaya line terminal. The final stage of the research involves analyzing the TRV simulation results and drawing conclusions.

A. Transient Recovery Voltage and Rate of Rise of Recovery Voltage Calculation

Transient Recovery Voltage (TRV) is the recovery voltage that appears across the terminals of a circuit breaker pole after current interruption. The TRV study is conducted to determine whether the circuit breaker can withstand this recovery voltage. The Rate of Rise of Recovery Voltage (RRRV) represents the slope or gradient of the TRV waveform and must also be considered, as it relates directly to how rapidly the TRV increases. Figure 1 illustrates the TRV phenomenon during the circuit breaker opening process. The Transient Recovery Voltage (TRV) value is determined by calculating the voltage difference between the two terminals of the circuit breaker at the instant of current interruption, where this voltage represents the transient response that occurs immediately after the current is interrupted. The voltage difference between the two terminals of the circuit breaker can be calculated as:

$$\text{TRV}(t) = U_1(t) - U_2(t) \quad (1)$$

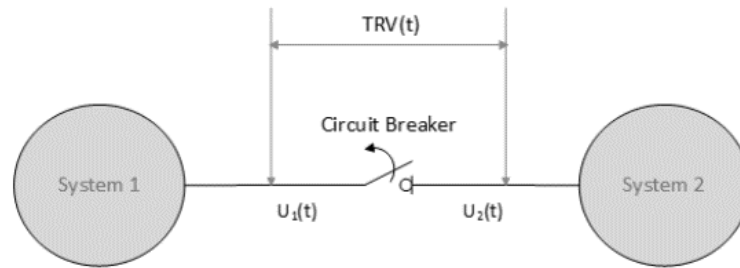


Figure 1. TRV During Circuit Breaker Opening [20]

U_1 and U_2 represent the voltages at the circuit breaker terminals connected to systems 1 and 2, respectively. When current interruption occurs at the circuit breaker, transient waves are generated. These transient waves arise from the system's transient response, which is associated with inductance and capacitance effects. The transient response is superimposed on the system's steady-state voltage waveform, and the combination of the two produces the total voltage response. TRV and RRRV are closely related to frequency, both from transient oscillations and the system voltage frequency. The oscillation frequency determines how rapidly the voltage rises (RRRV), which must be considered in TRV analysis. The oscillation frequency is influenced by capacitance and inductance. Equation 2 expresses the relationship between the frequency of the transient component and the corresponding capacitance and inductance values.

$$f_n = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

Where f_n is the frequency (Hz), L is the inductance (H), and C is the capacitance (F). When a circuit breaker operates on a transmission line with high inductance and very low stray capacitance, such as one that includes a series reactor, the system generates a high oscillation frequency. This rapid oscillation causes a fast voltage rise across the breaker terminals, resulting in a higher Rate of Rise of Recovery Voltage (RRRV).

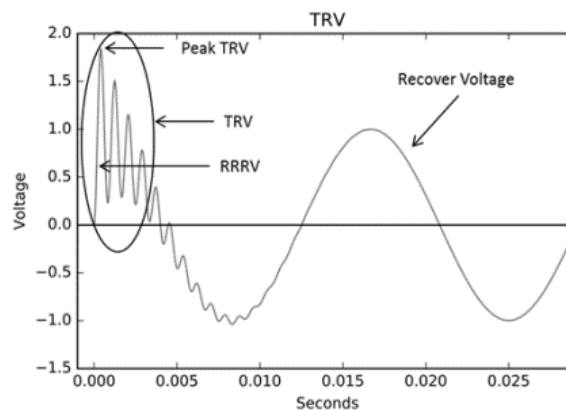


Figure 2. Illustration of Transient Recovery Voltage (TRV) and Rate of Rise of Recovery Voltage (RRRV) [20]

The Rate of Rise of Recovery Voltage (RRRV) is defined as the peak transient recovery voltage divided by the total time from zero voltage to the peak voltage [17]. It represents the rate at which the transient recovery voltage increases immediately after current interruption, reflecting how rapidly the voltage builds up across the circuit breaker contacts during the transient period. This parameter is a critical factor in evaluating a circuit breaker's performance,

as a higher RRRV indicates a faster voltage rise, which imposes greater electrical stress on the breaker's insulation and can affect its ability to interrupt fault currents safely and reliably.

$$f_n = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

Where the Rate of Rise of Recovery Voltage (RRRV) is expressed in kilovolts per microsecond (kV/μs), $V_{TRVFirstPeak}$ represents the first peak value of the transient recovery voltage in kilovolts (kV), t_{Peak} denotes the time at which the first TRV peak occurs in microseconds (μs), and t_0 corresponds to the time at zero voltage in microseconds (μs).

B. Modeling of the 500 kV Suralaya–Suralaya Baru Transmission Line

The Java–Madura–Bali power system model in this study follows the 2030 planning scenario specified in the RUPTL of PT PLN (Persero) 2021–2030 [21]. System modeling was performed using DlgSILENT PowerFactory 2021. Two configurations were developed: a baseline system without series reactors and a system with series reactors installed. The installation locations, quantities, and specifications of the series reactors implemented in the Java–Madura–Bali system are summarized in Table 1.

Table 1. Series Reactor Locations in the 500 kV Java–Madura–Bali System (2030)

Locations	Number of Series Reactor	Voltage (kV)	Frequency (Hz)	Impedance (Ohm)	Inductance (mH)
Suralaya-Suralaya Baru	2	500	50	20	63.66
Depok-Gandul	2	500	50	15	47.75
Cibinong-Depok	2	500	50	20	63.66
Cibinong-Tambun	2	500	50	20	63.66
Muara Tawar-Priok	2	500	50	20	63.66
Muara Tawar-Sukatani	2	500	50	20	63.66
Durikosambi-Kembangan	2	500	50	20	63.66
Muara Karang (IBT)	2	150	50	10	31.83
Cibinong (IBT)	2	150	50	5	15.92
Waru (IBT)	2	150	50	5	15.92
Priok (IBT)	2	150	50	5	15.92

Table 2. Equivalent Voltage Source (with Series Reactor)

Parameter	eqVac-0	eqVac-1
Voltage (kV)	500	500
Active Power (MW)	617.80725269	-1547.5183587
Reactive Power (MVar)	-78,878048251	-1025.1927386
V mag (p.u.)	0.9740275	0.9724346
R_1 (Ω)	3.8615938831	3.8051934853
X_1 (Ω)	19.201177985	14.671285987
R_2 (Ω)	3.479017523	3.8500502009
X_2 (Ω)	18.990602184	14.958877697
R_0 (Ω)	0.34444201691	0.4236695184
X_0 (Ω)	7.103579945	6.1842845633

This study focuses on the 500 kV Suralaya–Suralaya Baru transmission line for Transient Recovery Voltage (TRV) analysis. Since TRV analysis is local, the Java–Madura–Bali system is reduced to an equivalent model that includes only the target line. The 1.325-km line uses a 4-bundle ACSR Dove conductor and standard 500 kV type AA towers. Despite its short length, tower and conductor data are included to accurately represent mutual coupling effects. The reduced 2030 Java–Madura–Bali network provides the voltage levels and positive, negative,

and zero-sequence impedances listed in Table 2. Figure 3 shows the 500 kV Suralaya–Suralaya Baru transmission line model in DIgSILENT PowerFactory software after the network reduction process.

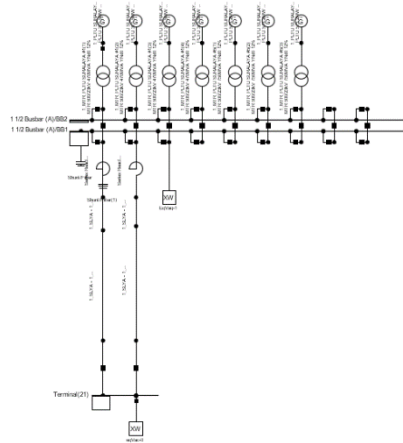


Figure 3. 500 kV Suralaya–Suralaya Baru Transmission Line with Series Reactor

Line coupling modeling is performed to evaluate the contribution of mutual inductance. In conducting the line coupling model, the calculation of the Geometric Mean Radius (GMR) is required. For a four-bundle conductor configuration, the GMR is expressed as follows:

$$D_s^b = \sqrt[16]{(D_s \times d \times d \times d \times 2^{1/2})^4} = 1,09^4 \sqrt{D_s \times d^3} \quad (4)$$

To calculate the average inductance per phase, the equation is:

$$L_a = 2 \times 10^{-1} \ln \frac{D_{eq}}{D_s} \text{ H/m} \quad (5)$$

Meanwhile, The Geometric Mean Radius (GMR) for a tubular conductor is determined using the following expression:

$$MR = r \cdot \exp \left[\frac{3q^2 - r^2}{4(r^2 - q^2)} - \frac{q^4}{(r^2 - q^2)^2} \cdot \ln \frac{r}{q} \right] \quad (6)$$

Where r is the outer conductor radius (mm), q is the inner conductor radius (mm), D_s^b is the GMR of the bundled conductor (m), D_s is the GMR of each subconductor (m), d is the spacing between subconductors (m), and L_a is the average inductance (H/m). Additionally, inductance may also result from series reactors installed in the transmission system.

In transmission lines, capacitance results from the coupling between conductor–conductor and conductor–ground. When two circuits are installed on the same tower, multiple capacitance components appear. For a standard tower configuration, four capacitance types are present: conductor to ground, interphase, intercircuit (unlike phases), and intercircuit (like phases). For extra-high-voltage lines with 4-bundle ACSR conductors, the line capacitance to neutral is given by:

$$C_N = \frac{2\pi k}{\ln(D_{eq}/r)} \quad (7)$$

Where r is the geometric mean radius (cm), D_{eq} is the equivalent spacing between bundle sub conductors (cm), and C_N is the capacitance to neutral (F/m).

C. Modeling of Short-Circuit Faults on the Transmission Line

The applied short-circuit fault is a single line-to-ground fault with a fault resistance of 0.1Ω and a short-circuit current of 9.284 kA at the circuit breaker, representing a short-line fault condition. The fault location is positioned very close to the series reactor and the circuit breaker on the 500 kV Suralaya–Suralaya Baru transmission line. The short-circuit fault in the line coupling model is implemented using a grounding switch.

D. Formation of the TRV Curve

The circuit breaker (CB) is ideally opened when the current reaches the zero-crossing point. However, in practice, the CB poles do not always open simultaneously (discrepancy), and there is a possibility that they open when the current is not at zero, resulting in a higher TRV peak during the opening process. The calculation standards for TRV and RRRV are defined in IEEE Std C37.011-2019 [11], which provides limits to ensure that breaker operation occurs safely without causing equipment damage. These limits are influenced by several factors, including the system voltage rating, the CB short-circuit current rating, the fault current being interrupted, the grounding method, the type of fault, and other system parameters. Two types of TRV curves are defined in the standard: the two-parameter curve and the four-parameter curve.

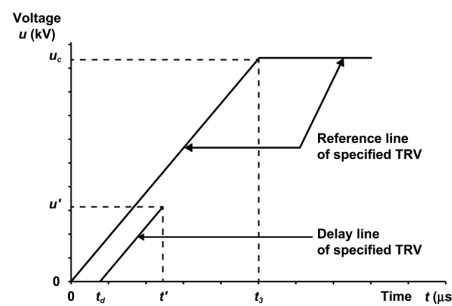


Figure 4. Two-parameter curve [11]

In the two-parameter TRV curve, the parameter u_c represents the peak TRV voltage measured in kilovolts (kV), while t_3 denotes the time required to reach u_c in microseconds (μs). The parameter u' corresponds to the reference voltage at the delay time (t_d), which marks the point before the transient recovery voltage begins to rise. The delay time (t_d) itself indicates the time interval, in microseconds, preceding the start of the TRV increase. Finally, t' represents the time at which the delay line intersects the TRV curve, also measured in microseconds (μs).

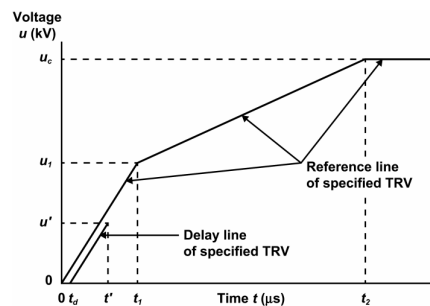


Figure 5. Four-parameter curve [11]

In the four-parameter TRV curve, u_1 represents the first reference voltage measured in kilovolts (kV), and t_1 denotes the time required to reach u_1 in microseconds (μs). The parameter u_c corresponds to the peak transient recovery voltage (kV), while t_2 indicates the time to reach u_c (μs). Additionally, u' is the reference voltage at the delay time (t_d), which defines the period

before the TRV rise begins. The delay time (t_d) represents the time interval, in microseconds, before the transient voltage starts to increase. Finally, t' is the time at which the delay line intersects the TRV curve, also measured in microseconds (μ s).

In this paper, the formation of the TRV curve for the 500 kV system refers to IEEE Std C37.011-2019 [11], using an interpolation method based on a circuit breaker short-circuit rating of 63 kA and a short-circuit current of 9.284 kA at the breaker. After calculating the TRV curve parameters, the curve is plotted using the Python programming language. This study focuses on the 500 kV Suralaya–Suralaya Baru transmission line for Transient Recovery Voltage (TRV) analysis. Since TRV analysis is local, the Java–Madura–Bali system is reduced to an equivalent model retaining only the target line.

E. Modeling of Stray Capacitance

In modeling the stray capacitance, typical data provided in IEEE Std C37.011-2019 [11] are used as reference. This study employs the average of the typical capacitance values to determine the stray capacitance parameters. The stray capacitance of the busbar is calculated by multiplying the number of bays by the busbar length and the number of busbars ($9 \times 35 \text{ m} \times 2$). The modeled stray capacitance values are $0.16476 \mu\text{F}$ for the busbar with a reactor and $0.0045 \mu\text{F}$ for the transmission line. One of the main challenges in stray capacitance modeling is obtaining detailed data on the quantity, capacitance value, and type of apparatus installed in substations or transmission lines, which is a common difficulty observed in TRV analysis.

F. Transient Recovery Voltage Simulation for the Suralaya–Suralaya Baru Transmission Line

The Transient Recovery Voltage (TRV) simulation for the Suralaya–Suralaya Baru 500 kV transmission line in 2030 was conducted based on the circuit breaker (CB) opening rule at random times, using the following formula:

CB Opening Time = 90 ms (minimum trigger time for CB) + 10 ms (maximum delay after fault initiation) + 5 ms (maximum opening discrepancy among CB poles after fault occurrence).

Thus, each phase has a random opening time with a discrepancy variation of 0–5 ms. This random CB opening approach is applied because the exact synchronization of breaker pole operations cannot be predicted. Consequently, the TRV analysis adopts a probabilistic approach, performing 100 simulation runs using DPL scripting in DIgSILENT PowerFactory software, with randomized CB opening times according to the defined rule. The TRV analysis results are finally represented as a histogram, illustrating the frequency distribution of TRV magnitudes over time.

RESULT AND DISCUSSION

In this section, the TRV simulation is performed without series reactors, using a single line-to-ground fault with a fault resistance of 0.1Ω . The fault is located at 5% from the sending end of the Suralaya transmission line. The circuit breaker opening discrepancy varies randomly between 0 and 5 ms, with a circuit breaker short-circuit rating of 63 kA. Figure 6 illustrates the TRV profile on the 500 kV Suralaya–Suralaya Baru transmission line in 2030 without the installation of series reactors. The graph shows that the 725–750 kV interval is the range in which TRV occurs most often, with a total of 47 events. The maximum TRV recorded is 872.9 kV, while the minimum is 703.7 kV. The corresponding RRRV value is $2.14 \text{ kV}/\mu\text{s}$.

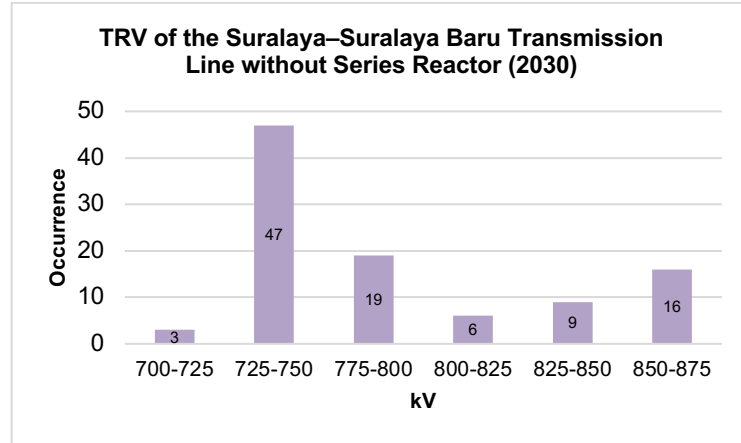


Figure 6. TRV without Series Reactor

Figure 7 shows that the TRV results with the addition of series reactors on the 500 kV Suralaya–Suralaya Baru transmission line in 2030 remain within the safe limit, at less than 998.88 kV, in accordance with the interpolation calculation described in IEEE Std C37.011-2019 [11]. The graph indicates that the voltage range of 800–825 kV represents the interval where TRV occurs most frequently, with 30 occurrences. A summary of the simulation results is presented in Table 3.

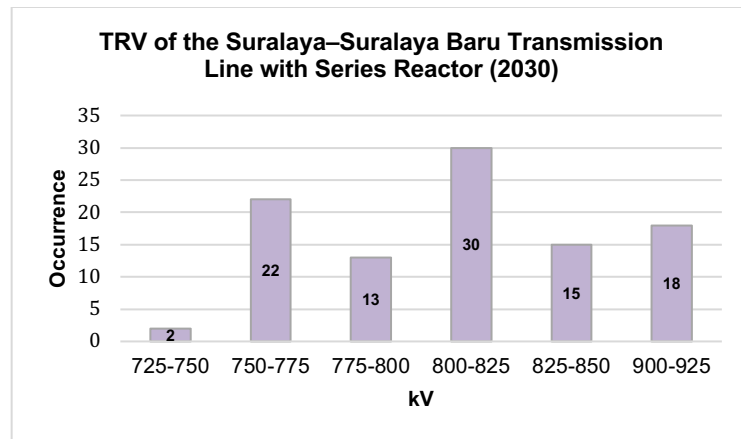


Figure 7. TRV with Series Reactor

Table 3 shows that the highest TRV value is 922.2 kV, while the lowest TRV value is 734.4 kV. Both TRV values remain within the calculated standard limits.

Table 3. TRV with Series Reactor (summary)

Transmission Line	Aspect Reviewed	TRV
Suralaya–Suralaya Baru with Series Reactor	Range with Highest Occurrence	800–825 kV
	Highest Occurrence	30 times
	TRV Maximum Value	922.2 kV
	TRV Minimum Value	734.4 kV
	TRV Limit	998.88 kV
	Exceeds Limit	No

Figure 8 presents the TRV simulation result corresponding to the highest simulated value of 922.2 kV. From the simulation plot, it is observed that the highest RRRV occurs in phase A. The RRRV value shown in Figure 5 is:

$$RRRV_{phaseA} = \frac{437.3494 \text{ kV}}{0.09958578 \text{ s} - 0.09954907 \text{ s}} = 11.9 \text{ kV}/\mu\text{s}$$

$$RRRV_{phaseB} = \frac{17.04599 \text{ kV}}{0.09754935 \text{ s} - 0.09750864 \text{ s}} = 0.4 \text{ kV}/\mu\text{s}$$

$$RRRV_{phaseC} = \frac{107.7371 \text{ kV}}{0.1074496 \text{ s} - 0.1073887 \text{ s}} = 1.8 \text{ kV}/\mu\text{s}$$

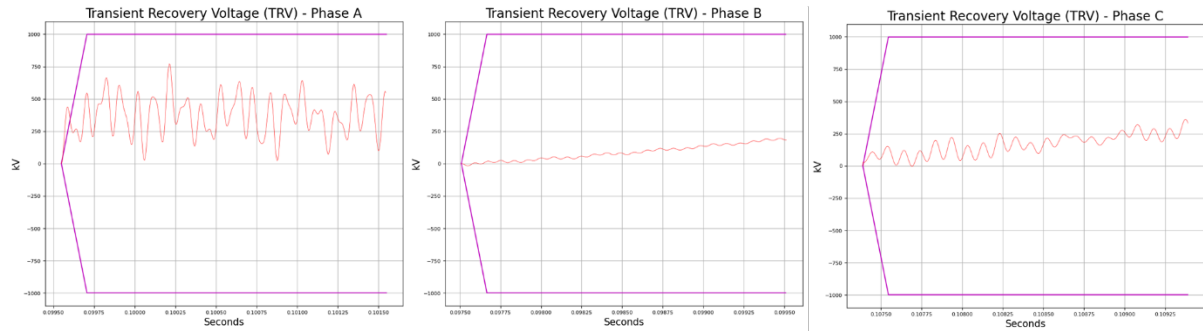


Figure 8. TRV and RRRV with Series Reactor

From these calculations, it can be observed that the RRRV value in phase A has exceeded the safe limit of 6.353 kV/ μ s. Based on the simulation results, it can be concluded that under the circuit breaker opening condition with the addition of series reactors in 2030, there is a potential for the RRRV value to surpass the standard limit during a single line-to-ground short-line fault. This condition indicates a possible risk of circuit breaker damage in the future. To mitigate high RRRV, methods such as capacitors, controlled switching, and pre-insertion resistors can be applied. Capacitors help by increasing system capacitance, which reduces the transient frequency and slows the rise of the recovery voltage. Controlled switching lowers switching-induced stresses by ensuring the circuit breaker operates at the most favorable point on the voltage waveform, preventing steep voltage changes. Pre-insertion resistors briefly add resistance during the switching process, damping high-frequency components of the transient and reducing both the TRV peak and the RRRV.

CONCLUSION

Based on the simulation results, the TRV and RRRV without series reactors were 872.9 kV and 2.14 kV/ μ s. After the installation of series reactors, the TRV increased to 922.2 kV and the RRRV rose significantly to 11.9 kV/ μ s. This indicates a potential risk of circuit breaker failure on the 500 kV Suralaya–Suralaya Baru transmission line in 2030, as the RRRV value exceeds the limit stated in IEEE Std C37.011-2019 [11] for a single line-to-ground short-line fault. Although the maximum TRV remains within the allowable range, the elevated RRRV surpasses the standard threshold. The TRV and RRRV characteristics are highly dependent on system capacitance and inductance, making detailed modeling essential. Factors such as stray capacitance and accurate transmission line representation are important because TRV is an electromagnetic transient phenomenon sensitive to these parameters. To reduce excessive RRRV, mitigation techniques such as capacitors, controlled switching, or pre-insertion resistors may be considered.

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