IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 12 Issue 01, January 2025
ISSN (Online) 2348 – 7968 | Impact Factor – 6.72
www.ijiset.com

Simulation of Transient Voltage and Current in The Switching Process of a Capacitor Bay Circuit Breaker at The 150 kV Substation Using EMTP

Afif Risanul Khoir[1], Muhamad Haddin[1]

[1]Electrical Engineering Department, Universitas Islam Sultan Agung,
Semarang, Indonesia

Abstract

This research investigates the simulation of transient voltages and currents during the CB switching process of a Capacitor Bay. The model comprises a CB unit with a Capacitor Bay connected to the substation busbar, with the load connected via a power transformer. The objective of this research is to determine the transient voltage and current on the busbar during capacitor bank circuit breaker switching operations. The defined parameters include: system voltage, source impedance, load impedance, damping reactor capacity, capacitor bank capacity, and switching timing. The research methodology involves collecting load data during peak load at 19:00 in November 2024, followed by acquiring nameplate data of the CB, damping reactor, and capacitor, as well as short-circuit current data. The Electromagnetic Transients Program (EMTP) is employed to simulate the research model. The research was performed at the 150 kV Kebasen Substation, Tegal, Indonesia. The research findings demonstrate that EMTP is a viable tool for simulating transient voltages and currents during the switching of the Capacitor Bay CB. The simulation results indicate that the highest transient voltages and currents occur when the CB closes synchronously across all three phases, coinciding with or near the peak of the voltage waveform, reaching 337.3 kV, which is 2.75 times the nominal peak voltage (122.4 kV), with a transient current of 1192.1 A, or 12 times the nominal peak current (96 A). Conversely, by implementing controlled CB switching timing according to the capacitor bank connection, specifically the ungrounded-Y configuration, transient voltages are eliminated within the system, and the transient current is reduced to 209.2 A, or 2.1 times the nominal peak current.

Keywords: *Transient voltage and current, Capacitor, CB, 150 kV Substation, EMTP.*

1. Introduction

A common issue encountered in long-distance 150 kV overhead transmission lines (OHTL) is voltage drop. This can be attributed to high loading, extended line lengths, and inadequate conductor specifications, consequently leading to increased power losses. A solution to mitigate this problem is the installation of capacitor banks. However, the operation of capacitor banks introduces a new challenge: the generation of transient voltages and currents during the switching of the Circuit Breaker (CB) to energize the capacitor bank. These transient disturbances progressively contribute to an increase in CB contact resistance, potentially inducing hotspot formation and consequently reducing the CB's operational lifespan. The 150 kV Kebasen Substation is equipped with a 25 MVAR capacitor bank operating at 150 kV, deployed based on system reactive power demand. Due to its location at the extremity of a subsystem, its classification as a switching substation with frequent subsystem reconfiguration, coupled with relatively low system voltage profiles, the capacitor bank at Kebasen experiences a significantly high operational frequency. To address this challenge, the implementation of a synchronized switching controller is proposed to precisely control the CB switching instants, thereby mitigating or eliminating the resulting transient over voltages and inrush currents.

Several prior investigations have addressed transient voltage and current phenomena associated with capacitor bay CB switching, including: simulations of capacitor switching within 150 kV systems with and without synchronized switching controllers [1], calculations of inrush current magnitudes and frequencies during capacitor bank energization [2], and power system modeling at RSI Sultan Agung Semarang utilizing Simulink Matlab software [3].

This research specifically focuses on the analysis of transient voltages and currents arising from capacitor bay CB switching. Simulations are conducted using the Electromagnetic Transients Program (EMTP), with the simulation model comprising a CB unit and associated capacitor bay connected to the substation busbar, with a load connected via a power transformer. The 150 kV Kebasen Substation, located in Tegal, Indonesia, serves as the case study.

2. Method

A substation serves as the interconnection point between the power generation system and the 150 kV transmission system, facilitating transmission interconnection and the transition from transmission to the 20 kV distribution system. Substations play a crucial role in the reliable and efficient delivery of electrical power from generating facilities to end-users. A substation comprises high-voltage electrical equipment designed for the transmission and regulation of electrical power flow; the equipment housed within a substation is termed main transmission equipment (MTE). The MTE in a substation typically includes: power transformers, current transformers (CTs), voltage transformers (VTs), circuit breakers (CBs), disconnectors (DSs), lightning arresters (LAs), busbars, and other secondary and auxiliary equipment. According to the International Electrotechnical Vocabulary (IEV) 441-14-20, a Circuit Breaker (CB) is defined as a mechanical switching device capable of closing, carrying, and interrupting load current under normal operating conditions, as well as being capable of closing, carrying (for a specified duration), and interrupting load current under abnormal/fault conditions, such as short circuits [4]. The specification data of the Capacitor Bay CB installed at the 150 kV Kebasen Substation is presented in Table 1.

Table 1: Specification data of the Capacitor Bay CB at the 150 kV Kebasen Substation

Parameter	Unit	Parameter	Unit
Circuit-breaker type	LTB1700/8	Operating device type	BLK222
No.	HSB0422056	No.	HS80422058-AT
Order	244039/10	Order	244039/10
Voltage	170 kV	Breaking current	40 kA
Insulation level		DC-component	53 %
Lightning impulse withstand voltage	750 kV	First-pole-to-clear-factor	1.5
Switching impulse withstand voltage	- kV	Making current	100 kA
Power frequency withstand voltage	325 kV	Short-time current	3s 40 kA
Frequency	50 Hz		
Normal current	3150 A	Line charging breaking current	50 A
Gas pressure (SF6)	Abs (+20ºC)	Mass total	655 kg
Max. working pressure	0.90 MPa	Mass of gas	9 kg
Filling	0.70 MPa	Rules	IEC 60056
Signal	0.62 MPa	Operating sequence	O-0.3s-CO-3m-CO
Blocking	0.60 MPa	Temperature class	-30°C
Volume per pole	65 L	Year of manufacture	2004

Capacitor banks are equipment utilized to enhance the quality of electrical energy supply, including: improving voltage at the load side, power factor correction, and reducing transmission losses. A drawback of capacitor bank application is the generation of harmonics during switching operations and the requirement for specialized CB or switching controller designs [5]. According to IEEE 1100-1999, a transient is defined as a disturbance within a sub-cycle of an alternating current (AC) waveform, characterized by abrupt and discontinuous waveform changes occurring within a short time frame [1]. Transient phenomena manifest as changes in voltage or current values, or both, over a specific duration departing from steady-state conditions. These phenomena originate from external or environmental factors, such as lightning strikes, as well as from system operations or internal factors, such as switching processes [2]. Transient current is defined as the magnitude of the initial current surge that appears in a circuit when the circuit is connected to a load. The transient current equation for the switching process of a single capacitor bank is given in Eq. (1).

$$I_{peak} = \sqrt{2}\sqrt{I_{sc}I_1} \qquad (1)$$

with I_{peak} = maximum transient current (A), I_{SC} = short-circuit current (A), I_1 = base current (A).

The short-circuit current (I_{SC}) value is obtained from the short-circuit current data of the GI/GITET Jawa Bali system in the second semester of 2024, issued by UP2B Jawa-Bali [8]. For the 150 kV Kebasen substation, the 3-phase short-circuit current is 7.47 kA, as shown in Table 2.

Tabel 2: Short-circuit current at 150 kV Kebasen Substation

Busbar	**Substation**	**UP2B**	Voltage	IHS KIT DMN ROB July 2024		IHS KIT Aktif ROB July 2024	
			kV	1ph(kA)	3ph(kA)	1ph(kA)	3ph(kA)
1	KEBASEN	UP2B Central Java & DIY	150	5.15	7.48	5.14	7.47
2	KEBASEN	UP2B Central Java & DIY	150	5.15	7.48	5.14	7.47

The base current (I_1) must be calculated before we can determine the transient current. Eq. (2) is used to calculate the base current.

$$I_1 = \frac{Q_C}{\sqrt{3}\,V} \qquad (2)$$

with I_1 = base current (A), Q_C = capacitor capacity (VAR), V = nominal voltage (V).

Switching operations of a circuit breaker (CB) in a power system induce transient voltage and current phenomena. The closure of a CB results in a significant inrush current with a duration on the order of microseconds to milliseconds. This peak current is commonly referred to as a transient current [2]. Energizing an initially uncharged capacitor can lead to a momentary short circuit condition, causing a substantial inrush current and a deep voltage dip in the system. The closing of a capacitor bank CB must be synchronized with the system voltage zero crossing to minimize the transient current. The closing sequence of a capacitor bank CB is dependent on the neutral grounding configuration of the capacitor bank. For a grounded-Y connection, as depicted in Figure 1, each phase is closed independently with a phase shift of 1/6 cycle or 30 electrical degrees (3.3 ms for a 50 Hz system).

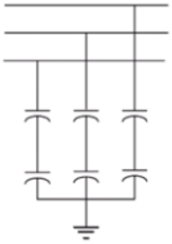


Fig. 1. Grounded-Y capacitor bank connection.

If the capacitor bank is ungrounded, the first two phases should be closed when the voltage difference between them is zero, while the third phase should be closed 1/4 cycle or 45 electrical degrees (5 ms for a 50 Hz system) after the other two phases. The ungrounded-Y connection of capacitors is shown in Figure 2.

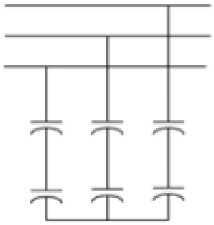
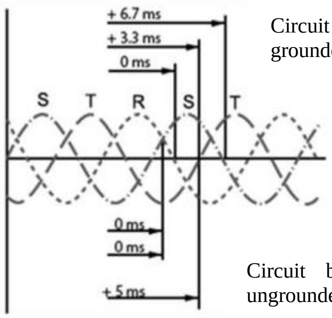


Fig. 2. *Ungrounded*-Y capacitor bank connection.

The switching sequence of the capacitor bank circuit breaker is depicted in Figure 3.



Circuit breaker closing procedure for grounded capacitor banks

Circuit breaker closing procedure for ungrounded capacitor banks

Gambar 3. *Switching* capacitor's CB.

To determine the parameter values used in the EMTP simulation model components, equations are required to convert field data into a format compatible with the EMTP model component parameters. EMTP utilizes voltage amplitude as a source parameter, and Eq. (3) is used to calculate the voltage amplitude (V_A).

$$V_A = \frac{\sqrt{2} \times V}{\sqrt{3}} \qquad (3)$$

with V_A = voltage amplitude (V), V = system voltage (V).

To determine the source impedance (Z_S), the short-circuit current data provided in Table 2 is required to calculate the MVASC. Eq. (4) and (5) are then used to determine the source impedance (Z_S).

$$MVA_{SC} = \sqrt{3} \times V \times I \qquad (4)$$

with MVA_{SC} = short circuit MVA, V = voltage (V), I = 3-phase short circuit current (A).

$$Z_S = \frac{kV^2}{MVA_{SC}} \qquad (5)$$

with Z_S = source impedance (Ohm), MVA_{SC} = *short circuit* MVA, kV = voltage (kV).

Given a power factor of 0.9, the impedance angle, resistance (R), and inductance (L) of the equivalent circuit model are determined using equations (6) to (9).

$$\delta = \cos^{-1} \alpha \qquad (6)$$

with δ = phase angle (º), α = power factor.

$$R = Z_S \cos \delta \qquad (7)$$

with R = resistance (Ohm), Z_S = source impedance (Ohm), δ = phase angle (º).

$$XL = Z_S \sin \delta \qquad (8)$$

with XL = inductive reactance (Ohm), Z_S = source impedance (Ohm), δ = phase angle (º).

$$L = \frac{X_L}{2\pi f} \qquad (9)$$

with L = inductance (H), XL = inductive reactance (Ohm), f = system frequency (Hz).

The calculation of the inductance value (L) for the damping reactor installed at the 150 kV Kebasen substation refers to Eq. (9), using the inductive reactance (XL) value as specified in Table 3.

Table 3. Specification data of capacitor bay damping reactor at 150 kV Kebasen substation.

Parameter	**Value**	**Unit**
Manufacturer	TRENCH LIMITED	
Equipment Type	CAPACITOR REACTOR	
Country of Manufacture	CANADA	
Serial Number	28221-2	
Total Weight	149	kg
Year of Manufacture	2004	
Number of Phases	1	
Type of Cooling	NATURAL AIR	
Measured Impedance	0.503	Ω
Measured Impedance	0.509	Ω
Frequency (FREQ)	50	Hz
Continuous Current	96	A
Thermal	2.4 kA 1 sec	
System Voltage	170	kV
BIL (Basic Impulse Level)	750	kV
Voltage Drop	0.048	kV
Mechanical Peak Current	6.12	kA
Specification Number & Year	IEC 289-1985	

Eq. (10) is employed to calculate the transformer ratio, which is defined as the ratio of the high-voltage side voltage to the low-voltage side voltage.

$$n = \frac{HV}{LV} \qquad (10)$$

with n = transformer ratio, HV = high-voltage side voltage (V), LV = low-voltage side voltage (V).

To determine the values of resistance (R) and inductance (L) on the 20 kV load side, which is used as a substitute for customer loads, as shown in Eq. (11) and (12).

$$R = \frac{\sqrt{3}\,.V^2}{MVA\,.\alpha} \qquad (11)$$

with R = resistance (Ohm), V = low-voltage side voltage (V), MVA = power (MVA), α = power factor.

$$L = \frac{\sqrt{3}V^2}{2\pi f MVA\,.sin\,(\cos^{-1}\alpha)} \qquad (12)$$

with L = inductance (H), f = frequency (Hz), MVA = power (MVA), α = power factor.

The 150 kV Kebasen substation is operated with 4 transformer units, each with a capacity of 60 MVA, with the average load in November 2024 as shown in Table 4.

Table 4. Capacity and load of the 150 kV Kebasen substation transformers.

Transformer	Capacity (MVA)	Load	
		%	MVA
1	60	63.2	37.92
2	60	65.8	39.48
3	60	48.1	28.86
4	60	56.2	33.72
Total			139.98

This research was conducted at the 150 kV Kebasen Substation, located at Jalan Raya II, Kebasen, Tegal, Indonesia. The capacitor bay was selected for analysis and simulation. To determine the transient voltage and current, a single line diagram, average monthly load data, and equipment nameplates were required. The 150 kV Kebasen Substation operates at a voltage level of 150 kV/20 kV, with the 150 kV side connected to the primary winding of the transformer and the 20 kV side connected to the secondary winding, from which power is distributed to customers through feeders. The single line diagram of the 150 kV Kebasen Substation is shown in Figure 4.

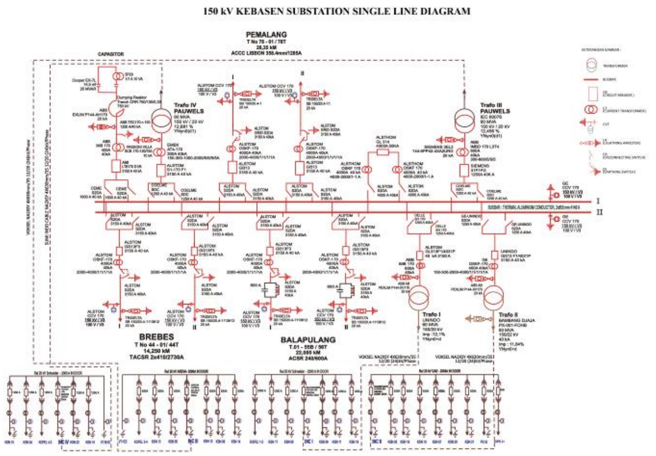
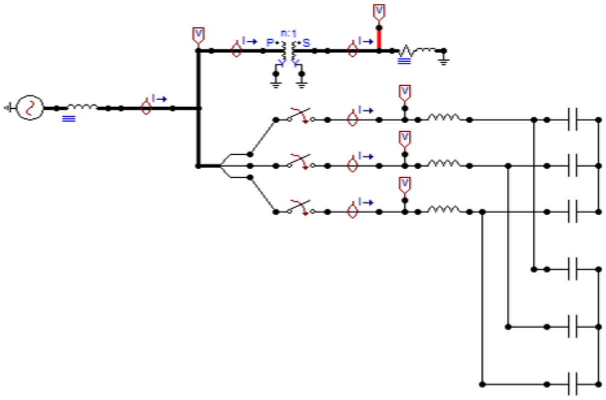


Fig. 4. 150 kV Kebasen substation Single Line Diagram.

The required data includes equipment specifications, monthly load data, and load and source impedance data. Based on the capacitor bank capacity data (Figure 4) and calculations using Eq. (13), circuit breaker (CB) specifications (Table 1), damping reactor specifications (Table 3) and calculations using equation (9), source impedance calculations using Eq. (1) and (2) and Table 2, and load impedance calculations based on the average November 2024 load data (Table 4) and Eq. (11) and (12), the data is then processed and modeled in the ATPDraw software for simulation, as shown in Figure 5.



Gambar 5. ATPDraw model for the 150 kV Kebasen substation.

The research methodology consisted of several phases, visually represented in Figure 6.

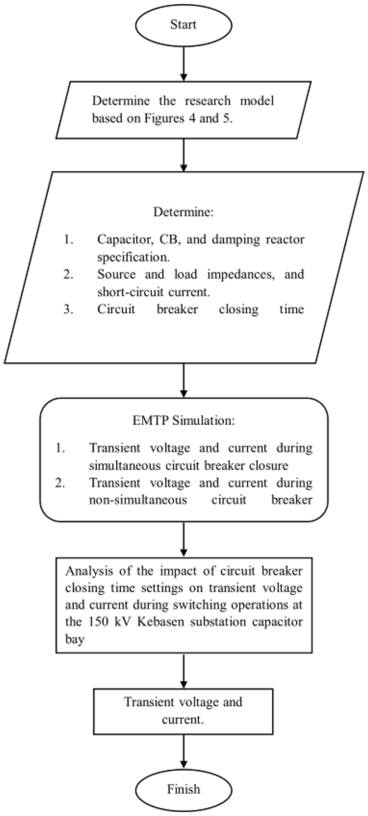


Fig. 6. Research flowchart.

3. Results and Analysis

By determining the research model based on Figures 4 and 5, and utilizing data from the capacitor specifications, circuit breaker (CB) parameters (Table 1), damping reactor (Table 3), source and load impedances (Table 2), short circuit current (Table 2), and simultaneous and non-simultaneous CB closing times, calculations were performed using equations (1) and (2) and Table 2. Subsequently, transient voltage and current simulations were conducted for both simultaneous and non-simultaneous CB closing scenarios to evaluate the system's response under different operating conditions.

3.1 The Calculation of Transient Current

Referring to Eq. (1) and (2) and Table 2, the base current (I_1) and peak transient current (I_{peak}) are determined as follows.

$$I_1 = \frac{25 \times 10^6}{\sqrt{3} \times 150 \times 10^3}$$

$$I_1 = 96{,}22 \text{ A}$$

By utilizing Eq. (1), the peak transient current (I_{peak}) can be determined. The short-circuit current values, as presented in Table 2, were obtained from the short-circuit current data for the Java-Bali GI/GITET system in the second semester of 2024, published by UP2B Jawa-Bali [8]. For the 150 kV Kebasen substation, the three-phase short-circuit current is 7.47 kA.

$$I_{peak} = \sqrt{2}\sqrt{7{,}47 \times 10^3 \times 96{,}22}$$

$$I_{peak} = 1198{,}96\ A$$

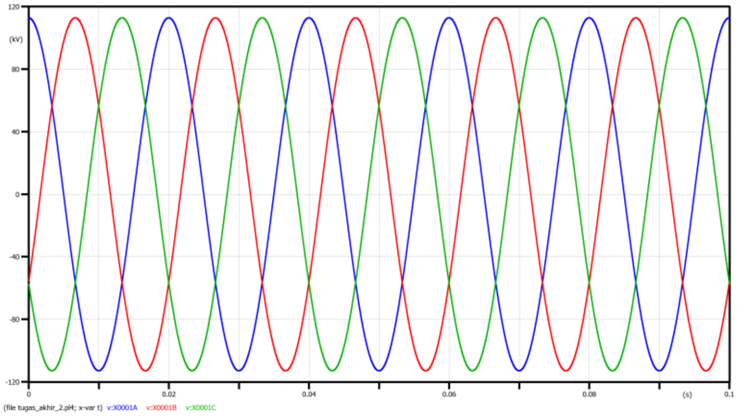
The transient current experienced by the circuit breaker (CB) of the capacitor bay during switching operations is 1198.96 A, which is 12 times the base current of the capacitor bay, which is only 96.22 A.

3.2 EMTP Simulation

Based on the simulation results referring to the research model in Figure 6, the values and waveforms of transient voltage and current during simultaneous and non-simultaneous circuit breaker (CB) closing operations were obtained. The simulation was conducted under two different conditions: simultaneous CB closure and non-simultaneous CB closure with specific timing settings according to the ungrounded-Y capacitor switching configuration.

3.2.1 Simulation of Simultaneous Circuit Breaker Closure

In field conditions, the exact timing of circuit breaker (CB) switching relative to the voltage or current waveform is often uncertain. However, in this simulation, the CB closing time (T-cl) is assumed to occur at the peak of the voltage waveform. Figure 7 illustrates the voltage waveform.



Gambar 7. Three phase voltage waveform at busbar.

Figure 7 shows that there are multiple points where the voltage waveform reaches its peak. For this simulation, two peak points at 0.02 s and 0.04 s on the R-phase voltage waveform were selected as sample points. The simulation results for the case where the circuit breaker closes simultaneously at 0.02 s are presented in Figures 8 and 9.

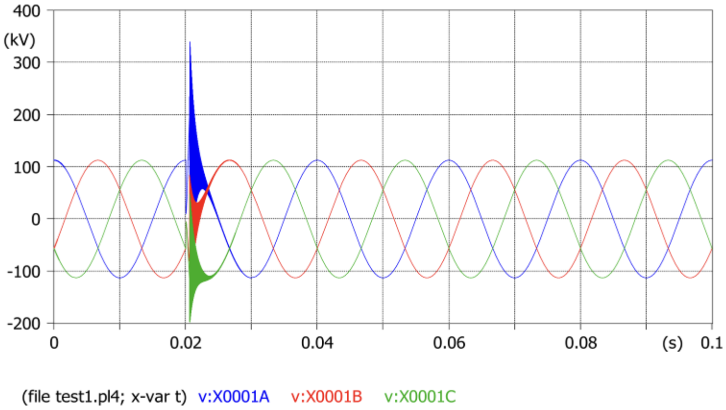


Fig. 8. Transient voltage simulation results for a circuit breaker closing time of 0.02 s.

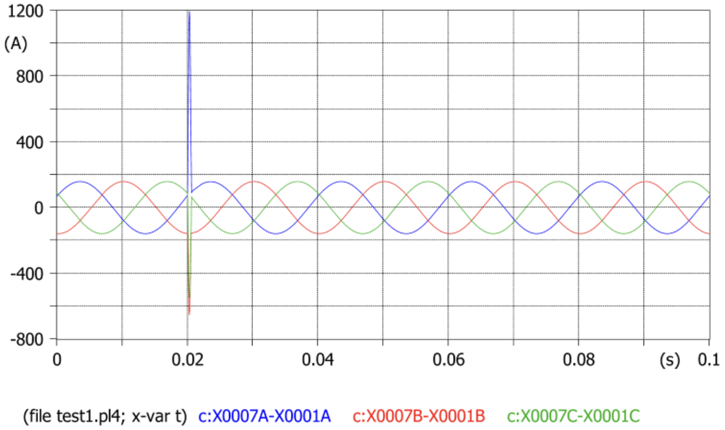


Fig. 9. Transient current simulation results for a circuit breaker closing time of 0.02 s.

The simulation results for simultaneous circuit breaker closure at 0.0 seconds are presented in Figures 10 and 11.

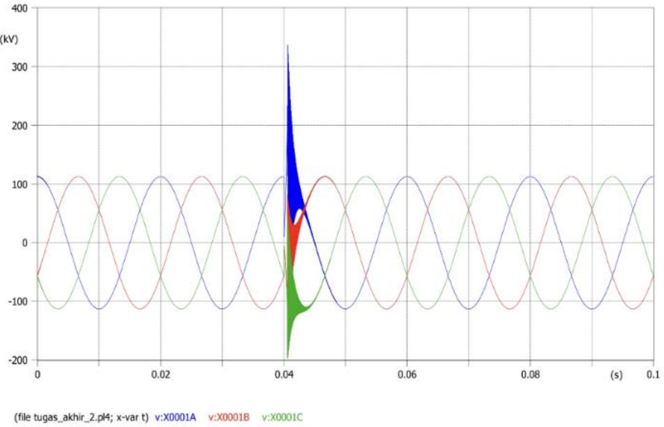


Fig. 10. Transient voltage simulation results for circuit breaker closing time of 0.04 s.

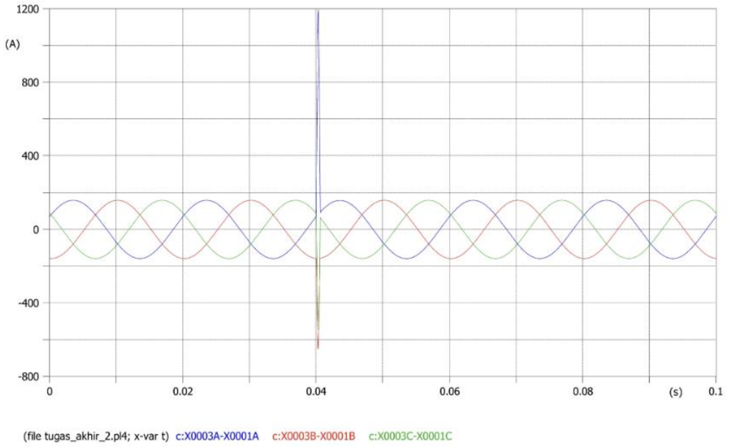


Fig. 11. Transient current simulation results for a circuit breaker closing time of 0.04 s.

3.2.2 Simulation of Asynchronous Circuit Breaker Closure

To determine the circuit breaker (CB) closing time (T-cl), the closing sequence is adjusted according to the capacitor connection type. Since the 150 kV Kebasen substation uses an ungrounded wye connection, the first two phases are closed when the voltage difference between them is zero, while the third phase is closed 1/4 cycle or 45 electrical degrees (5 ms for a 50 Hz system) after the other two phases. Based on the voltage waveform characteristics in Figure 7, the switching time (T-cl) is set at 0.043 seconds, when phases R and S cross each other, resulting in a zero voltage difference. Subsequently, phase T is closed 1/4 cycle or 45 electrical degrees (5 ms for a 50 Hz system) after phases R and S. The simulation results for this condition are presented in Figures 12 and 13.

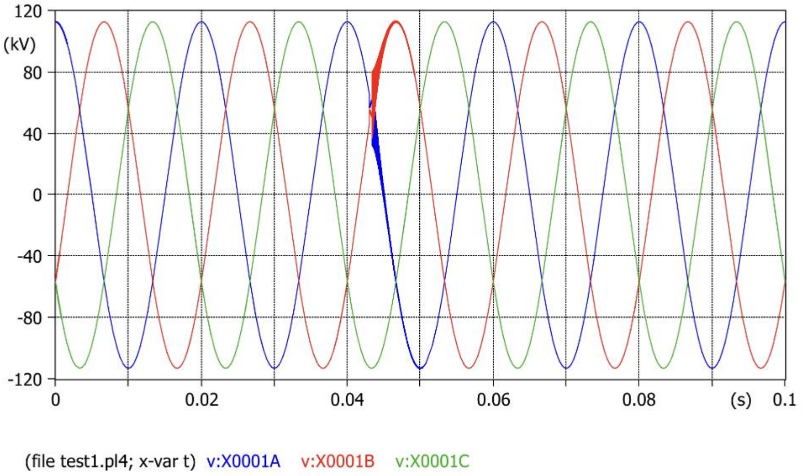


Fig. 12. Voltage simulation results for asynchronous circuit breaker closure.

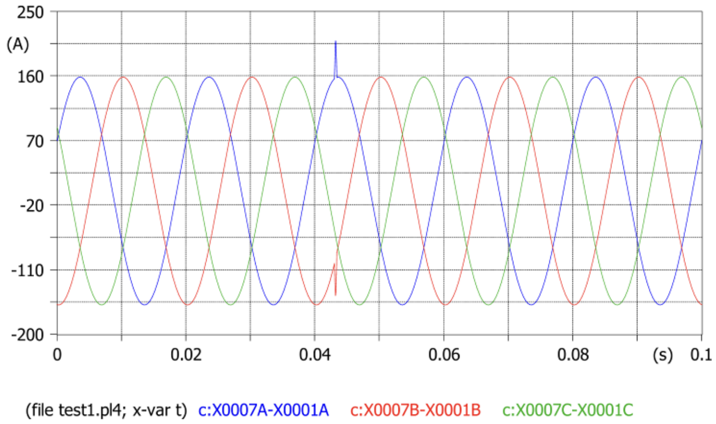


Fig. 13. Current simulation results for asynchronous circuit breaker closure

3.3 Analysis

Based on calculations using equation (1), the maximum transient current is determined to be 1198.96 A, which is 12 times the nominal current. Simulation results show that the circuit breaker closing time significantly affects the magnitude of transient currents and voltages in the system. As the circuit breaker closing time approaches the peak of the voltage waveform, the resulting transient current and voltage magnitudes increase. Table 5 presents the simulation results for simultaneous circuit breaker closure.

Table 5. Simulation results for simultaneous circuit breaker closure

Switching time	**Transient voltage (kV)**			**Transien current (A)**		
	R	S	T	R	S	T
T-cl = 0.02 s	**337,3**	159,1	197,3	**1.192,1**	650,6	548,2
T-cl = 0.04 s	**337,3**	156,5	197,1	**1.192,1**	650,9	547,8

Table 5 shows that the highest transient voltage and current occur in phase R, where the circuit breaker closing time coincides with the peak of the R-phase voltage waveform. The maximum transient voltage is 337.3 kV, which is 2.75 times the nominal voltage, while the maximum transient current is 1192.1 A, which is 12 times the nominal phase current. Table 6 presents the simulation results for asynchronous circuit breaker closure.

Table 6. Simulation results for asynchronous circuit breaker closure.

Switching time	**Transient voltage (kV)**			**Transient current (A)**		
	R	S	T	R	S	T
T-cl = 0.043	113.2			209.2		
T-cl = 0.043		113.2			158.8	
T-cl = 0.048			113.2			158.8

Table 6 shows that when the circuit breaker (CB) closing time is adjusted according to the ungrounded-Y capacitor connection, the resulting transient voltage and current are significantly reduced. In this scenario, no transient voltage is observed, and the transient current is limited to 209.2 A, which is only 2.1 times the nominal current. Based on the circuit breaker nameplate data (Table 1), with a nominal voltage of 170 kV and an impulse level (BIL) of 750 kV, and a nominal current of 3150 A, the equipment can withstand the observed transient levels. However, frequent switching operations may reduce the lifetime and performance of the equipment, especially the circuit breaker, due to the repetitive exposure to transient conditions, as indicated in Table 7.

Table 7. CB contact resistance test results

Year	**Phase (μΩ)**			**Standard (μΩ)**
	R	S	T	
2023	55.7	58.6	45.5	40
2024	62.7	62	62.9	

Table 7 indicates a degradation in the circuit breaker's contact resistance performance. This can lead to anomalies such as the formation of hotspots within the circuit breaker chamber, which may cause insulation failure and increased power losses due to the higher contact resistance.

4. Conclusions

The calculation and simulation results lead to the following conclusions:

1. Calculation results show that the peak transient current during the capacitor switching process is 1198.96 A, which is 12 times the nominal peak current.
2. When all circuit breakers close simultaneously without any timing coordination, the simulation results indicate that the transient voltage reaches 2.75 times the peak nominal voltage (337.3 kV), and the transient current reaches 12 times the peak nominal current (1192.1 A). However, by adjusting the circuit breaker closing times based on the ungrounded-Y capacitor connection, transient voltages can be eliminated, and transient currents can be significantly reduced to 209.2 A, or 2.1 times the peak nominal current.
3. Although the installed circuit breaker is capable of withstanding the transient voltage and current caused by switching operations, frequent switching can degrade the contact resistance, as indicated by the test results in Table 7. The contact resistance has increased from a maximum of 58.6 μΩ in 2023 to 62.9 μΩ in 2024, exceeding the standard value of 40 μΩ for ABB LTB170 D1/B circuit breakers. This degradation can lead to the formation of hotspots and potential insulation failure.

References

[1] Thaha. Sharma, “A Study on the Application of Switching Controllers for High Voltage Capacitors,” (Indonesian Language) *Tesis Program Studi Teknik Elektro Program Pascasarjana Universitas Hasanuddin Makassar*, 2014.

[2] M. Adif, Soemarwanto, and M. Dhofir, “Analysis of Inrush Current during Capacitor Bank Switching at Manisrejo Madiun Substation,” (Indonesian Language) *Jurnal Mahasiswa TEUB, Vol. 2, No. 5*, 2014.

[3] Febrie Ardiyanto, Dedi Nugroho, and Jenny Putri Hapsari, “Analysis of Inrush Current during Capacitor Bank Switching at Manisrejo Madiun Substation,” (Indonesian Language) Transmisi, 22, (4), Oct. 2020.

[4] Anonymous, Capacitor Maintenance Manual, (Indonesian Language) Jakarta: PT PLN (Persero), 2014.

[5] Anonymous, Circuit Breaker Maintenance Manual, (Indonesian Language) Jakarta: PT PLN (Persero), 2014.

[6] Anonymous, Guidelines and Instructions for Transmission and Substation Protection Systems in Java-Bali, (Indonesian Language) Jakarta: PT PLN (Persero) P2B Jawa-Bali, 2013.

[7] Hans Kristian Høidalen, László Prikler, and Francisco Peñaloza, ATPDraw version 7.2 for Windows Users Manual, Norwegia, 2020.

[8] Anonymous, Short-circuit Current of GI/GITET System in Java-Bali for The Second Semester of 2024, (Indonesian Language) Jakarta: PT PLN (Persero) UIP2B Jawa-Bali, 2024.

Afif Risanul Khoir is a bachelor's degree student in electrical engineering at Universitas Islam Sultan Agung, Semarang, Indonesia. He has a strong interest and is currently a practicing expert in high and extra-high voltage electrical protection and maintenance.

Muhamad Haddin is a Profesor, senior lecturer at Universitas Islam Sultan Agung, Semarang, Indonesia. He obtained his Bachelor's degree in Electrical Engineering from Universitas Diponegoro, Semarang. His academic journey continued with a Master's degree in Electrical Engineering from Universitas Gadjah Mada, followed by a Doctor in Electrical Engineering from the Sepuluh November Institute of Technology. He is research interests revolve around high voltage and electrical power systems. His academic background and expertise contribute significantly to advancing knowledge and understanding in these areas.