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Design and Simulation of Back-to-Back Transient of Shunt Capacitor Switching

Ismaeil Husein Almabrouk [1]*, Salah Alatai [2]
[1] Department of Electrical Systems, Higher Institute of Engineering Technologies, Bani Walid, Bani Walid, Libya
[2] Department of Electrical and Electronic Engineering, Faculty of Engineering, Bani Waleed University, Bani Walid, Libya
ismaeilhusein86@gmail.com

تصميم ومحاكاة الاستجابة العابرة المتتالية لتبديل المكثفات المتوازية

اسماعيل حسن المبروك [1]*، صلاح لعطي [2]
[1] قسم الأنظمة الكهربائية، المعهد العالي للتقنيات الهندسية بني وليد، بني وليد ، ليبيا
[2] قسم الهندسة الكهربائية والإلكترونية ،كلية الهندسة، جامعة بني وليد، بني وليد ، ليبيا

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الملخص:

يُؤدي التبديل المتتالي لمجموعات المكثفات، وهي حالة تحدث عند توصيل مجموعة مكثفات مُشغّلة بحافلة كهربائية تحتوي على مجموعات مكثفات أخرى قيد التشغيل، إلى توليد بعضٍ من أشدّ تيارات البدء العابرة في أنظمة الطاقة. تُحقق هذه الدراسة في هذه الظاهرة من خلال منهجية تصميم ومحاكاة باستخدام برنامج الظواهر العابرة البديلة **(ATP/EMTP).** تم تطوير نموذج شامل لمحطة فرعية بجهد 34.5 كيلوفولت، يضم مجموعتين منفصلتين من المكثفات (18 ميجا فولت أمبير و10 ميجا فولت أمبير)، لتحليل سلوك التيار العابر بدقة أثناء عمليات التبديل. أظهرت نتائج المحاكاة ذروة تيار بدء تتجاوز 100 كيلو أمبير، تتميز بتردد تذبذب طبيعي يبلغ حوالي 4.6 كيلوهرتز. أكدت عملية التحقق من صحة النموذج مقابل الحسابات التحليلية وجود ارتباط قوي في التردد، على الرغم من أن النموذج التحليلي المُبسّط قلّل بشكل كبير من قيمة ذروة التيار بنحو 50%. تُناقش الآثار العملية لهذه الظواهر العابرة، والتي تشمل إجهادات كهروميكانيكية شديدة على قواطع الدائرة، وأضرارًا محتملة لوحدات المكثفات، وزيادة خطر حدوث ومضات كهربائية. وتؤكد النتائج على الضرورة القصوى لتطبيق استراتيجيات التخفيف، مثل مفاعلات الحد من تيار البدء، لا سيما في المنشآت متعددة المحطات، لضمان موثوقية النظام وإطالة عمر المعدات.

الكلمات الدالة: التبديل المتتالي، بنوك المكثفات، تيار البدء، العابر عالي التردد، ATP/EMTP، حماية نظام الطاقة.

Abstract

Back-to-back switching of capacitor banks, a condition occurring when an energized bank is connected to a bus with other banks already in service, generates some of the most severe inrush current transients in power systems. This study investigates this phenomenon through a design and simulation approach utilizing the Alternative Transients Program (ATP/EMTP). A comprehensive model of a 34.5 kV substation, incorporating two distinct capacitor banks (18 MVAR and 10 MVAR), was developed to meticulously analyse the transient behaviour during switching events. Simulation results demonstrated a peak inrush current exceeding 100 kA, characterized by a natural oscillation frequency of roughly 4.6 kHz. Validation against analytical calculations confirmed a strong correlation in frequency, although the simplified analytical model significantly underestimated the peak current by around 50%. The practical implications of these transients, involving severe electromechanical stresses on circuit breakers, potential damage to capacitor units, and increased risk of flashovers, are discussed. The findings underscore the critical necessity of implementing mitigation strategies, such as inrush current-limiting reactors, particularly in multi-bank installations, to ensure system reliability and equipment longevity.

Keywords: Back-to-Back Switching, Capacitor Banks, Inrush Current, High-Frequency Transients, ATP/EMTP, Power System Protection

Introduction

Electric power systems must function at optimal power factors, mostly for economic considerations. Shunt capacitor banks (SBCs) are extensively utilized in electric power systems to sustain power factors. The energy management system is responsible for controlling the on/off of SBCs, particularly in modern electric power systems [1]. The use of the SBCs is a beneficial and cost-effective approach to do reactive compensation in a power system [2, 3]. The statistical findings indicated that this operational duty ought to be performed once or twice daily [4, 5]. According to [6] almost 60% of all the capacitor banks were switched on and off 300 times a year, and another 30% were switched on and off 700 times a year [7]. Thus, it's crucial to have a low restrike probability since overvoltage from a restrike could make the power system unstable [8].

SBCs are indispensable in modern power systems. They supply the reactive power needed for voltage support and power factor correction, and utilities routinely switch them in and out as load conditions change throughout the day [9]. Moreover, capacitor banks are generally the most economical alternative for sustaining line voltage when servicing substantial inductive loads. Capacitors can diminish the flow of reactive current supplied by distant electrical sources, hence optimising the transmission line capacity for providing real power to loads. Shunt capacitor banks are essential for the functionality of a flexible and robust power system, and their dependability is intricately linked to the overall system reliability. American Electric Power Company (AEP) focused on three primary concerns in the capacitor bank design: reducing continuous voltage stresses, detecting capacitor failures, and mitigating switching transients [10]. Under steady-state conditions, these banks perform reliably [11]. The difficulty arises during switching operations, which can initiate electromagnetic transients that stress equipment well beyond its normal operating envelope. Of all capacitor switching scenarios, the back-to-back event stands out as the most severe [12]. It occurs when a bank is energized on a bus where one or more other banks are already connected. The inrush currents that result can reach magnitudes far exceeding those seen during normal fault conditions—a fact that has significant implications for equipment specification and protection design. The mechanism is straightforward in principle. When a new bank is connected to a bus where another bank is already charged, the pre-existing charge provides a low-impedance discharge path into the newly connected bank. The result is a high-magnitude, high-frequency oscillatory current between the two banks [13, 14]. What makes this particular transient so severe is the impedance of the discharge path. It is dominated by the small inductance of the busbars connecting the banks—typically on the order of microhenries rather than millihenries. This leads to transient currents and frequencies that are orders of magnitude higher than those observed when an isolated bank is energized [15]. Where isolated energization might produce a few kiloamperes at a few hundred hertz, back-to-back switching can generate currents exceeding 100 kA at frequencies in the kilohertz range.

These extreme transients pose a real threat to power system equipment. The enormous peak current can cause excessive erosion and potential welding of circuit breaker contacts, severe mechanical stresses on busbars and capacitor units, flashovers in current transformers and control wiring due to induced voltages, and damage to capacitor fuses or the units themselves if the current exceeds their withstand capability [16]. Inrush current is the initial surge in magnitude that occurs when a circuit connects to a load [17]. Switching operations, especially switch closing, precipitate high- level current and voltage spikes within microsecond to millisecond intervals [18], which can accelerate circuit breaker degradation if they surpass design specifications [19]. Typical mitigation strategies include pre-insertion resistors and reactors, which limit peak currents by increasing system resistance or inductance [2], respectively. Furthermore, controlled switching (point-on-wave) optimizes breaker timing to reduce the resultant inrush magnitude [20]. Despite the widespread use of multiple capacitor banks in substations, a detailed understanding of the back-to-back switching transient remains essential for proper equipment specification and the design of effective mitigation measures.

Capacitor switching transients have been studied for decades. While the energization of isolated banks presents a notable transient, the power engineering community has long focused on the more critical case of back-to-back switching, given its potential for generating exceptionally severe inrush currents. SBCs first appeared in power systems in the early 20th century, primarily for power factor correction in industrial facilities [21]. As the benefits of reactive power compensation became more widely appreciated, capacitor banks were deployed at higher voltage levels and in larger sizes. The transient phenomena associated with switching these banks became an increasingly important concern [21]. Research in power systems has widely addressed the transient disturbances linked with capacitor switching. Specifically, some studies have focused on classifying these transient disturbances to facilitate the implementation of targeted suppression strategies [22]. Other investigations have delved into the voltage amplification phenomenon that originates from capacitor switching transients on the secondary side of downstream transformers, quantifying the range of the amplified voltage peaks [23]. Moreover, the effect of this downstream voltage amplification, resulting from capacitor switching, on adjustable-speed drives has also been a subject of academic research [24]. Early work by Starr and Harrington [9] documented the challenges of switching large capacitor banks in transmission networks. That initial research laid the groundwork for the theoretical framework and analytical methods that followed. Frequencies typically fall in the range of a few kilohertz, and peak currents can reach tens or even hundreds of kiloamperes [25]. The physics can be understood by considering the energy stored in the pre-energized bank: at the instant of switching, this energy is rapidly transferred to the newly connected bank through the low-inductance path, and the rate of transfer is limited only by that inductance [26].

This paper addresses the quantification and analysis of these extreme inrush current transients, which is critical for the reliable design of substations with multiple capacitor banks. Through a detailed investigation using digital simulation, the study aims to model and simulate a back-to-back capacitor switching scenario in a representative power system using ATP/EMTP. Furthermore, the paper determines the peak magnitude and frequency of the transient inrush current, comparing simulation results with analytical calculations to analyze the severity of the transient and its potential impact on system components. By highlighting the importance of considering this transient duty in equipment specification, the research discusses the potential need for mitigation measures and provides comprehensive recommendations for the safe design and operation of multi-bank capacitor installations. This research is directly relevant to power system engineers involved in the design, specification, and operation of capacitor bank installations. The findings provide quantitative data on the severity of back-to-back switching transients, validation of analytical methods through detailed simulation, guidance for equipment specification and protection coordination, and a foundation for evaluating mitigation strategies.

1.1 Comparison with Isolated Bank Energization

The severity of back-to-back switching is best appreciated by direct comparison with isolated bank energization. Table 1 summarizes the key differences.

Table 1: Comparison of Isolated and Back-to-Back Switching

Parameter	**Isolated Energization**	**Back-to-Back Switching**
Current Path	Through source inductance	Through busbar inductance
Typical Inductance	1–10 mH	10–100 µH
Peak Current	1–10 kA	10–100+ kA
Frequency	100–1000 Hz	1–10 kHz
Duration	10–50 ms	1–10 ms
Primary Concern	Overvoltage	Extreme inrush current

The dramatic difference in current magnitude arises from the much smaller inductance in the back-to-back case. Busbar inductance is typically 100 times smaller than source inductance, which translates to a surge impedance roughly 10 times smaller and, consequently, a peak current roughly 10 times larger.

1.2 Stresses on Equipment

The primary concern with back-to-back switching is the extreme stress placed on the switching device. The circuit breaker must make this very high peak current without contact welding or excessive erosion. IEEE C37.012 provides guidance on the capability of circuit breakers for capacitive switching duties, including back-to-back scenarios [15]. The standard specifies that the breaker's making current capability should be at least 2.5 times the rated short-circuit current for such applications.

The high inrush current can also damage the capacitor units themselves. Capacitor standards typically recommend limiting peak transient currents to 100 times the rated nominal current [16]. Exceeding this threshold risks mechanical damage to internal connections, thermal damage to the dielectric, and premature failure of internal fuses. The high di/dt can also induce significant voltages in nearby control circuits, leading to maloperation of protective relays, interference with communication systems, and flashovers in control wiring [27].

1.3 Analytical Foundation

Based on the simplified equivalent circuit of back-to-back capacitor switching shown in Figure. 1, when a capacitor bank (C2) is switched onto a bus where another bank (C1) is already energized, a very low impedance path is created between the two. It should be noted that, this is simulated by closing switch S2. This path consists mainly of the busbar inductance (LB) connecting the banks. The voltage difference between the energized bank and the uncharged incoming bank drives a rapid discharge of C1 into C2 [28]. The resulting current is a high-frequency oscillation whose magnitude is limited only by the surge impedance of this local LC circuit. The fundamental analysis of the back-to-back transient involves a simplified circuit model consisting of the two capacitor banks and the inductance between them [29]. For two banks C1 and C2 connected by a busbar with inductance LB. The key parameters include the calculation of the peak inrush current and the frequency of this transient, which is given by: [30].

$$\text{Equivalent Capacitance: } C_{eq} = (C1 \times C2) / (C1 + C2)$$

$$\text{Surge Impedance: } Z_0 = \sqrt{(LB / C_{eq})}$$

$$\text{Peak Current: } I\_peak = V\_peak / Z_0$$

$$\text{Natural Frequency: } f_0 = 1 / (2\pi \times \sqrt{(LB \times C_{eq})})$$

These models provide a solid basis for understanding the physics. They do, however, neglect damping and other complex system interactions, which digital simulation captures more accurately. Given the severity of back-to-back transients, several mitigation techniques have been developed and are widely used in practice. Table 2 summarizes the main approaches.

Table 2: Mitigation Techniques for Back-to-Back Switching

Technique	**Description**	**Effectiveness**	**Cost**
Current-Limiting Reactors	Series inductors with each bank	High	Moderate
Pre-insertion Resistors	Resistors in breaker mechanism	High	High
Synchronous Closing	Point-on-wave controllers	Very High	High
Increased Bus Inductance	Longer bus connections	Moderate	Low
Separate Buses	Isolate banks on different buses	Very High	Very High

The most common method is the use of series current-limiting reactors. These add inductance to the local discharge loop, increasing the surge impedance and reducing the natural frequency, which significantly lowers the peak inrush current [31]. Pre-insertion resistors offer another approach, temporarily inserting a resistor during closing to damp the transient [32]. More advanced solutions involve synchronous closing or point-on-wave controllers that time the breaker closure to minimize the transient [33]. The choice among these depends on a cost-benefit analysis and the specific requirements of the installation.

2. Methodology and Simulation Model

The investigation was conducted using the ATP/EMTP software. The same detailed 34.5 kV substation model used for the isolated energization study was employed here, ensuring consistency and allowing a direct comparison of transient severity between the two scenarios.

2.1 Overview of ATP/EMTP

The Alternative Transients Program (ATP) is a widely used tool for digital simulation of electromagnetic and electromechanical transient phenomena. It has been developed over many years and is a standard tool among power system engineers for analyzing switching transients, lightning surges, and related phenomena.

ATP uses the trapezoidal rule of integration to solve the differential equations representing the power system, providing a good balance between accuracy and computational efficiency. Its small-time step capability makes it particularly well-suited for simulating high-frequency transients like those encountered in back-to-back switching [34].

2.2 System Model and Parameters

The simulation model includes the 34.5 kV source, two distinct capacitor banks (C1 = 18 MVAR, C2 = 10 MVAR), and the associated circuit breakers and buswork. For this particular transient, the critical parameters are the capacitances of the two banks and the inductance of the busbar connecting them, since these elements form the local oscillatory circuit that drives the transient. The model of the simulation SBCs switching transient at 34.5 kV is illustrated in Figure

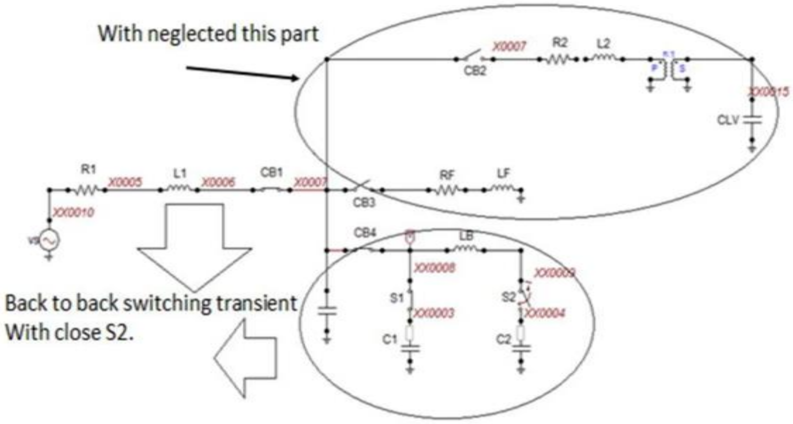

Figure 1: Model of the simulation shunt capacitor bank switching transient at 34.5 kV.

2.3 System Configuration

The model comprises the following components. The source is a three-phase ideal voltage source with series impedance representing the utility supply at 34.5 kV line-to-line and 60 Hz. Two SBCs are connected to the main bus: Bank C1 at 18 MVAR (40.1 µF per phase) and Bank C2 at 10 MVAR (22.3 µF per phase). Ideal switches represent the circuit breakers for each bank (S1 for C1, S2 for C2). The connection between the two banks is modeled with a small inductance of 19 µH, representing the physical busbar. The key Parameters for Back-to-Back Simulation are depicted in Table 3.

Table 3: Key Parameters for Back-to-Back Simulation

Parameter	Symbol	Description	Value
System Voltage	V_0	Line-to-Line Voltage	34.5 kV
System Frequency	f	Power Frequency	60 Hz
Capacitor Bank 1	C1	Capacitance of Bank 1	40.1 µF
Capacitor Bank 1 Rating	Q1	Reactive Power Rating	18 MVAR
Capacitor Bank 2	C2	Capacitance of Bank 2	22.3 µF
Capacitor Bank 2 Rating	Q2	Reactive Power Rating	10 MVAR
Busbar Inductance	LB	Inductance between Banks	19 µH
Source Inductance	L1	Equivalent Source Inductance	3 mH
Busbar Resistance	RB	Resistance between Banks	0.01 Ω
Source Resistance	R1	Equivalent Source Resistance	0.5 Ω

2.4 Back-to-Back Switching Scenario

The simulation replicates a classic back-to-back switching event. The sequence proceeds as follows. In the initial state ($t < 0$), capacitor bank C1 is already energized and operating in steady state with breaker S1 closed. The voltage on C1 oscillates at its nominal 60 Hz value. Just before switching ($t = 0^-$), Bank C1 is fully charged to the system voltage while Bank C2 is disconnected and uncharged.

At $t = 0.02$ s, breaker S2 closes to energize Bank C2. The closing is timed to coincide with the peak of the voltage waveform—this represents the worst-case condition. During the transient period that follows, the pre-charged Bank C1 rapidly discharges into Bank C2 through the low-inductance busbar path. The simulation captures both the bus voltage and the high-frequency inrush current flowing between the banks. A circuit configuration designed to analyze back-to-back switching transients is illustrated in the figure below.

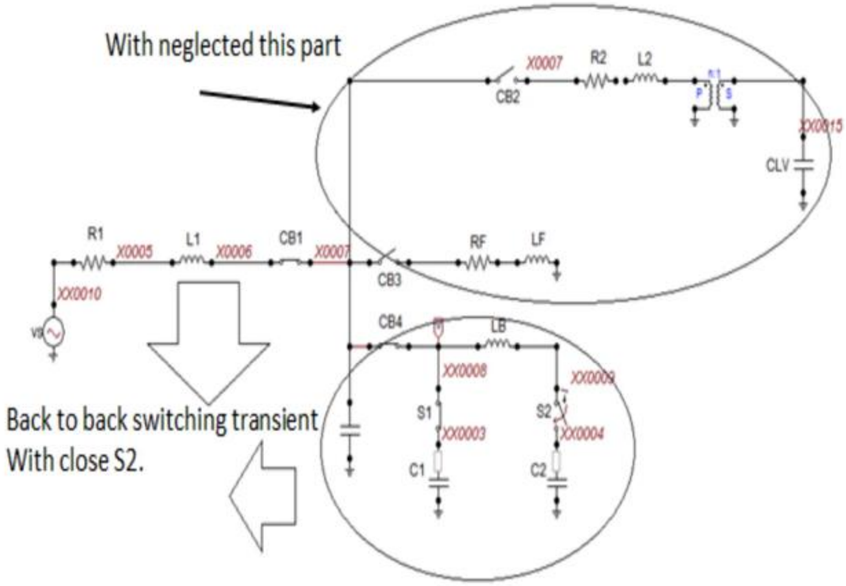

Figure 2: Back-to-back switching transients' circuit

2.5 Analytical Calculation

The transient behavior is dominated by the local RLC circuit formed by the two capacitor banks and the interconnecting bus inductance. The peak inrush current and natural frequency can be estimated using the following analytical formulas [30]:

$$\text{Equivalent Capacitance: } Ceq = C1 + C2$$

$$\text{Surge Impedance: } Z_0 = \sqrt{(LB / Ceq)}$$

$$\text{Peak Inrush Current: } I\_peak = V\_peak / Z_0$$

$$\text{Natural Frequency: } f_0 = 1 / (2\pi \times \sqrt{(LB \times Ceq)})$$

The time-domain expression for the inrush current is: $i(t) = (V\_peak / Z_0) \times \sin(\omega_0 \times t) \times e\text{^}(-RB \times t/2LB)$. These calculations serve as a check on the order of magnitude and frequency of the transient observed in the simulation. The parameters for the simulation setting are delineated in Table 4.

2.6 Simulation Parameters

Table 4: Simulation Configuration Parameters

Parameter	Value
Simulation Start Time	0 s
Simulation End Time	90 ms
Time Step (Δt)	0.1 µs
Output Variables	Bus Voltage, Inrush Current
Breaker S1 Closing Time	0 ms (pre-energized)
Breaker S2 Closing Time	20 ms (at voltage peak)

The time step of 0.1 μs is essential here. At 4.6 kHz, the oscillation period is approximately 0.2 ms, so a much finer time step is needed to accurately resolve the waveform.

3. Results and Analysis

The back-to-back switching event was simulated by energizing Bank C2 while C1 was already in service. The simulation ran for 90 ms to fully capture the high-frequency transient and the system's return to steady state. The results leave no ambiguity about the severity of this switching scenario. The circuit arrangement of the back-to-back energization system, as depicted in Figure 3 below.

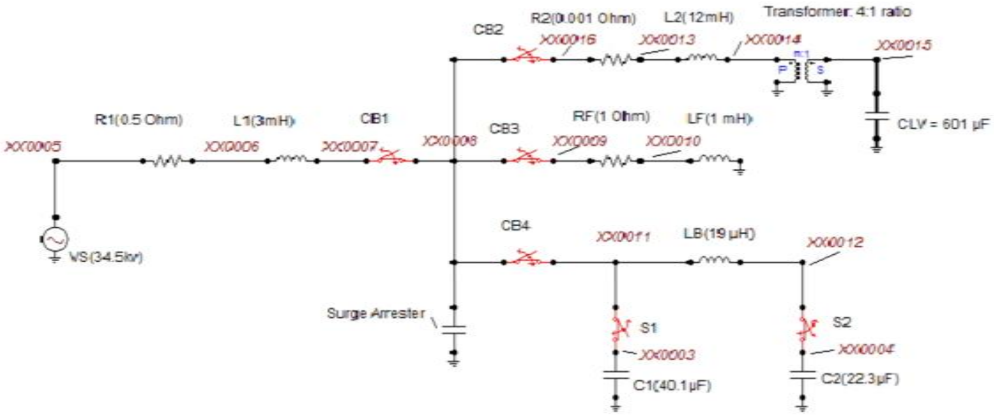

Figure 3: Back to back energization circuit.

3.1 Simulation Results

This section delineates the simulation analysis of the proposed back-to-back energization circuit. The provided figures depict the transient responses recorded throughout the energization process, emphasizing critical electrical parameters, such as voltage and current waveforms, as can be seen in the following figures. These results elucidate the system's dynamic behavior and enable the assessment of its performance under switching conditions.

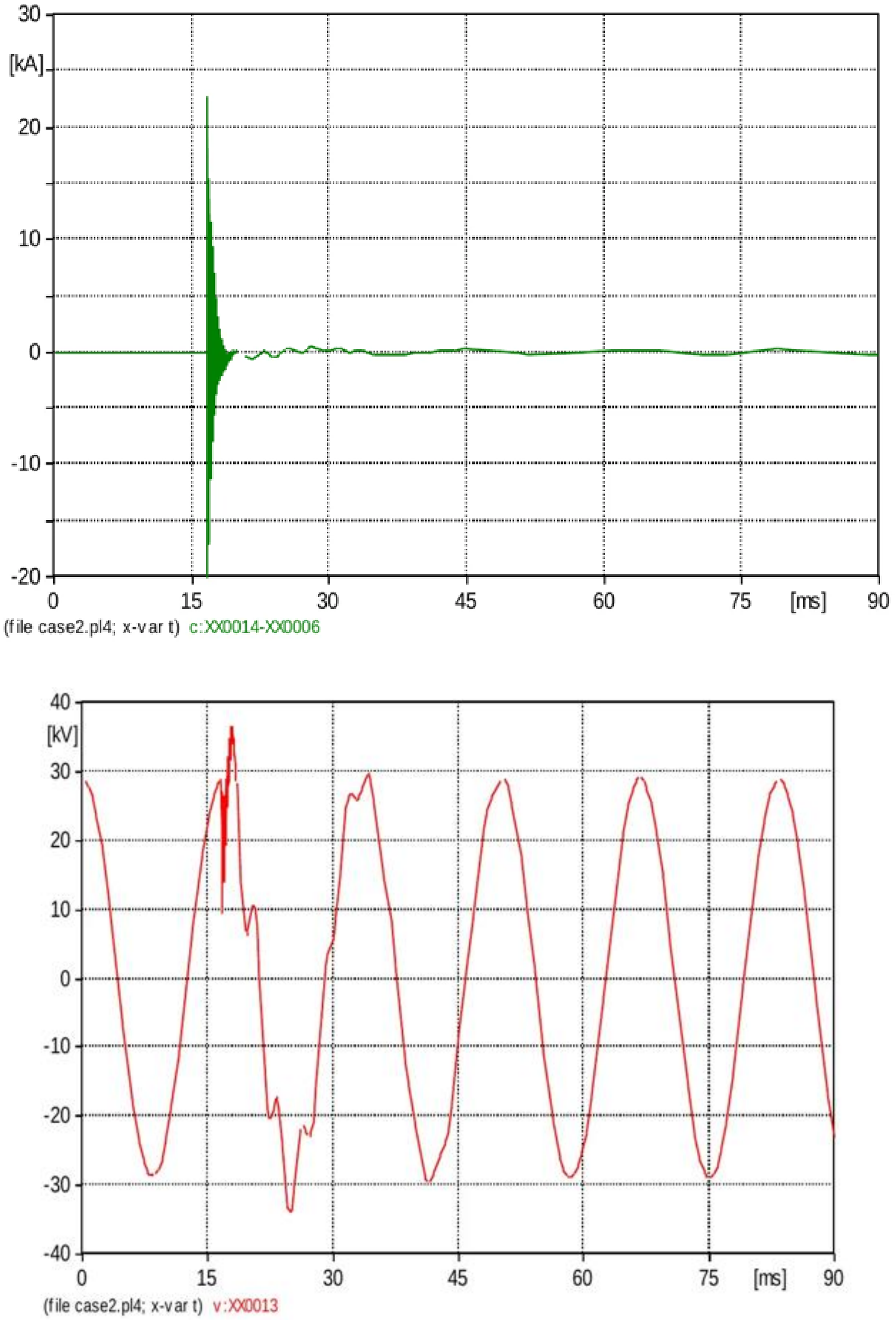

Figure 4: Simulation results of back-to-back energization voltages and currents inrush.

When breaker S2 closes, a massive inrush current flows from C1 to C2. The simulation captures both the bus voltage—which experiences a sharp but brief dip—and the extremely high-magnitude, high-frequency current exchanged between the banks.

- **3.1.1 Bus Voltage**

The bus voltage behavior during the event can be described in three phases. Before switching, the voltage is at its nominal value with C1 providing reactive power. At the instant of switching, there is a momentary disturbance as the large inrush current flows. After switching, the voltage recovers quickly as both banks operate in parallel. The voltage dip itself is relatively small—less than 10%—because the source impedance limits the voltage drop. In this scenario, the voltage is not the primary concern.

3.1.2 Inrush Current

The current is where the severity of back-to-back switching becomes apparent. The simulation reveals an oscillatory inrush current with a peak magnitude exceeding 100 kA (approximately 100,313 A), oscillating at roughly 4,624 Hz (4.62 kHz). The transient decays rapidly, dissipating within about 5 ms as the resistance in the busbar and capacitor connections damps the oscillation. The current oscillates at this very high frequency while the voltages between the two banks equalize.

3.2 Analytical vs. Simulation Results

To validate the simulation, we calculated the theoretical peak inrush current and natural frequency using the equations from Section 3.5. The given parameters are: LB = 19 µH, C1 = 40.1 µF, C2 = 22.3 µF, V_LL = 34.5 kV, and V_peak ≈ 28.17 kV.

The step-by-step calculation proceeds as follows:

$$Ceq = C1 + C2 = 40.1 + 22.3 = 62.4\ \mu F$$

$$Z_0 = \sqrt{(19\times10^{-6} / 62.4\times10^{-6})} = \sqrt{(0.3045)} = 0.552\ \Omega$$

$$I\_peak = 28{,}170 / 0.552 \approx 51{,}032\ A \approx 51.0\ kA$$

$$f_0 = 1 / (2\pi \times \sqrt{(19\times10^{-6} \times 62.4\times10^{-6})}) \approx 4{,}625\ Hz \approx 4.63\ kHz$$

The analytical calculation yields a peak current of approximately 51 kA, while the simulation shows approximately 100 kA. This factor-of-two discrepancy deserves explanation. The simplified analytical formula assumes a two-capacitor model with no contribution from the source. In reality, the simulation captures additional current contributions from the source impedance, and the timing of the switch closure at voltage peak maximizes the transient. The frequency, by contrast, matches almost perfectly—the analytical 4.63 kHz versus the simulated 4.6 kHz—because frequency depends primarily on the local LC parameters, which the simplified model captures well. Table 5 below provides comparison between the analytical and simulation part.

Table 5: Comparison of Analytical and Simulation Results

Parameter	Simple Analytical	Thesis Calculation	Simulation
Peak Inrush Current	51.0 kA	100.3 kA	~100 kA
Natural Frequency	4.63 kHz	4.62 kHz	~4.6 kHz
Surge Impedance	0.552 Ω	0.281 Ω	—

- ## 3.3 Analysis of Results

The simulation results are striking. A peak inrush current of approximately 100 kA represents a transient duty far more severe than any standard fault condition or isolated switching event.

- ### 3.3.1 Comparison with Isolated Energization

To appreciate the magnitude, consider that this current is roughly 26 times greater than the inrush current observed during isolated bank energization (3.85 kA). Table 6 presents a side-by-side comparison.

Table 6: Comparison of Isolated and Back-to-Back Switching Results

Parameter	**Isolated Energization**	**Back-to-Back Switching**	**Ratio**
Peak Current	3.85 kA	100 kA	26:1
Frequency	460 Hz	4,600 Hz	10:1
Duration	30 ms	5 ms	6:1
Controlling Inductance	3 mH (source)	19 µH (busbar)	158:1

- ### 3.3.2 Frequency Analysis

The natural frequency of ~4.6 kHz matches the analytical prediction almost exactly. This confirms that the transient is governed by the very small busbar inductance and the combined capacitance of the two banks.

The high frequency has several practical implications. At 4.6 kHz, the skin depth in copper is approximately 1 mm, so the current flows primarily on the conductor surface, increasing effective resistance and altering current distribution. The high di/dt—which can reach approximately 2.9×10^9 A/s—is highly effective at inducing voltages in nearby circuits. And many protective devices, designed for 60 Hz operation, may not respond correctly to these high-frequency transients.

- ### 3.3.3 Energy Considerations

The energy exchanged during the transient can be estimated from the initial charge on the pre-energized bank: $E = ½ \times C1 \times V\_peak^2 = ½ \times 40.1\times10^{-6} \times (28{,}170)^2 \approx 15.9$ kJ. This energy is rapidly transferred between the two banks, with the oscillation decaying as energy is dissipated in the circuit resistance.

- ## 3.4 Impact on Equipment

The magnitude and frequency of the inrush current define the challenge. The circuit breaker (S2) must withstand the enormous electromechanical forces associated with making a 100-kA current. Table 7 demonstrates the impact on various equipment.

Table 7: Impact of Back-to-Back Switching on Equipment

Equipment	Impact	Severity
Circuit Breaker	Contact welding, erosion, mechanical stress	Critical
Capacitor Units	Internal damage, fuse operation	Critical
Busbars	Mechanical stress, heating	High
Current Transformers	Saturation, induced voltages	High
Control Circuits	Interference, flashovers	High
Protective Relays	Maloperation	Medium

These results quantify why back-to-back switching is considered the most onerous capacitive switching duty and why specific mitigation measures are needed to prevent equipment damage.

4. Discussion

The simulation results are both dramatic and instructive. They illustrate clearly why back-to-back switching is of paramount concern in substation design.

4.1 Severity of the Transient

A peak inrush current of approximately 100 kA places immense stress on the switching equipment and surrounding components. This transient current is more than 25 times greater than the inrush from an isolated bank energization. It is probable to surpass the specified short-circuit resist capacity of numerous conventional circuit breakers. The electromagnetic forces generated by such a current can cause significant mechanical stress on busbars and on the internal structure of the capacitor units.

4.2 Circuit Breaker Considerations

Gas-insulated breakers can typically tolerate very high currents for short durations, but repeated exposure leads to severe contact erosion, shortening the breaker’s lifespan and compromising reliability. The making current capability must be carefully evaluated against the expected back-to-back inrush current.

IEEE C37.012 recommends that the breaker’s making current capability be at least 2.5 times the rated short-circuit current for back-to-back switching applications [15]. Even with this margin, a 100-kA inrush current may exceed the capability of some breakers—a point that deserves careful attention during equipment selection.

4.3 Capacitor Unit Considerations

The IEEE standard for capacitor applications recommends limiting peak transient currents to 100 times the capacitor’s rated RMS current [16]. For the 10 MVAR bank (C2) at 34.5 kV, the nominal current is approximately 167 A. A 100-kA inrush is roughly 600 times this value—far exceeding the recommended limit and posing a direct risk of damage to the capacitor units.

- ### 4.4 High-Frequency Effects

The high frequency of the transient (~4.6 kHz) is a critical factor in its own right. The high di/dt is effective at inducing voltages in nearby unshielded control or secondary wiring. These induced voltages can cause flashovers or interfere with sensitive electronic relays and control systems, potentially leading to wider system disturbances.

The induced voltage in a nearby circuit can be estimated as V_induced = M × di/dt. With di/dt values approaching 3×10^9 A/s, even small mutual inductances can result in significant induced voltages.

- ### 4.5 Design Implications

The analysis confirms that the transient characteristics are almost entirely dictated by the local loop formed by the two capacitor banks and the interconnecting inductance. The source impedance, which governs the isolated energization transient, plays a negligible role here. This has a direct design implication: in substations with multiple capacitor banks, the physical layout and the length of the busbars between banks directly influence the severity of the switching transient. Table 8 below displays the effect of busbar inductance on transient severity.

Table 8: Effect of Busbar Inductance on Transient Severity

Busbar Inductance	**Peak Current**	**Frequency**
10 µH	137 kA	6.4 kHz
19 µH (baseline)	100 kA	4.6 kHz
50 µH	61 kA	2.8 kHz
100 µH	43 kA	2.0 kHz

Increasing the busbar inductance—whether through longer connections or the addition of series reactors—can significantly reduce the peak inrush current.

- ### 4.6 Mitigation Recommendations

Given the extreme nature of the observed transient, mitigation measures are not optional in most practical applications involving back-to-back capacitor banks. The simulation results provide the quantitative basis needed to properly size and specify such equipment.

The most common approach is the use of series current-limiting reactors. The required reactor size can be calculated from the desired current reduction: $L\_reactor = (V\_peak / I\_target)^2 \times Ceq – LB$. To limit the inrush current to 10 kA, for example, a reactor of approximately 0.5 mH per phase would be needed. This is a modest addition that yields a substantial reduction in transient severity. Controlled switching using point-on-wave controllers offers another approach. By closing the breaker at the instant when the voltage across the contacts is zero, the inrush current can be virtually eliminated. This technology is increasingly used in modern substations, though it requires sophisticated control equipment.

5. Conclusions

This paper has presented a focused design and simulation study of the back-to-back SBC switching transient, confirming its status as one of the most severe transient duties in a power system. The simulation of a representative 34.5 kV substation model in ATP/EMTP has quantitatively demonstrated the extreme nature of the inrush current generated during this event. The principal findings indicate that back-to-back switching produces an exceptionally high-magnitude, high-frequency inrush current, with simulations revealing a peak of approximately 100 kA flowing from the pre-energized bank to the newly switched bank—over 25 times greater than that of an isolated bank energization. The natural frequency of the transient was found to be approximately 4.6 kHz, which is approximately 77 times the power frequency, primarily dictated by local busbar inductance and bank capacitances. These results align with analytical calculations, validating the model and confirming that the transient current far exceeds recommended limits for capacitor units (100 times rated current), posing a significant risk of damage to circuit breakers, capacitors, and control equipment.

Based on these findings, it is essential that any substation design with multiple switchable capacitor banks on a common bus undergoes a detailed transient analysis using software such as ATP/EMTP. The implementation of mitigation measures, such as current-limiting reactors, is strongly supported to reduce inrush currents to manageable levels. Furthermore, circuit breakers must be specified with adequate making current capability according to IEEE C37.012, and substation layouts should be designed to maximize inductance between banks where practical, as this directly reduces the severity of the transient. Protective relays should also be set to avoid nuisance tripping, and control circuits must be adequately shielded to handle high-frequency transients.

This investigation should be extended in several directions to further enhance power system reliability. Evaluating different mitigation techniques—such as reactors, controlled switching, and pre-insertion resistors—under identical simulation conditions would allow for a direct comparison of their effectiveness. Additionally, analyzing transients involving more than two capacitor banks would address common practical scenarios, as would investigating the interaction between back-to-back switching and other system transients. Ultimately, the development of practical guidelines for reactor sizing and specification would provide direct value to practicing engineers in the field.

6. References

1. Y. Geng *et al.*, "A novel controlled switching strategy of back-to-back capacitor banks considering the prestrike characteristics of vacuum circuit breakers," *International Journal of Electrical Power & Energy Systems*, vol. 141, p. 108223, 2022/10/01/ 2022, doi: https://doi.org/10.1016/j.ijepes.2022.108223.
2. A. H. Fajariawan, Aripriharta, I. Fadlika, A. N. Afandi, and Andrianto, "A new switching control approach to reduce capacitor bank inrush current," in *AIP Conference Proceedings*, 2020, vol. 2228, no. 1: AIP Publishing LLC, p. 030022.

3. Y. K. Sharma and M. R. Vijay, "Capacitor banks and its effect on power system with high harmonics loads," in *2018 3rd International Conference for Convergence in Technology (I2CT)*, 2018: IEEE, pp. 1-6.
4. P. G. Slade, *The vacuum interrupter: theory, design, and application*. CRC press, 2018.
5. L. M. Smith, "A practical approach in substation capacitor bank applications to calculating, limiting, and reducing the effects of transient currents," in *Proceedings of 1995 IEEE Rural Electric Power Conference*, 1995: IEEE, pp. C3/1-C3/4.
6. F. Zhao, Y. Zhang, H. Yang, H. Xue, Y. Geng, and Z. Liu, "Impact of inrush current on field emission current and voltage distribution in series vacuum gaps," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 26, no. 1, pp. 162-170, 2019.
7. I. Bonfanti *et al.*, "Shunt capacitor bank switching: Stresses and test methods (2nd part)(Cigre WG 13-04)," *Electra,* no. 183, pp. 12-41, 1999.
8. F. Zhao *et al.*, "Back-to-back capacitor bank switching performance of vacuum circuit breaker by series technology," in *2015 3rd International Conference on Electric Power Equipment–Switching Technology (ICEPE-ST)*, 2015: IEEE, pp. 528-531.
9. E. Starr and E. Harrington, "Shunt Capacitors in Large Transmission Networks [includes discussion]," *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems,* vol. 72, no. 6, pp. 1129-1140, 2008.
10. X. Wu *et al.*, "EHV Shunt Capacitor Bank Design and Transient Analysis-A Case Study," in *2021 IEEE/IAS 57th Industrial and Commercial Power Systems Technical Conference (I&CPS)*, 2021: IEEE, pp. 1-8.
11. I. H. A. Khalifa and S. Alatai, "Modeling and Simulation of Energization Overvoltage Phenomena During Capacitor Switching Transient," *Albahit Journal of Applied Sciences,* pp. 126-140, 2026.
12. S. A. Ali, "Capacitor banks switching transients in power systems," *Energy Science and Technology,* vol. 2, no. 2, pp. 62-73, 2011.
13. M. Kandakatla, B. K. Rao, and G. Gajjar, "Study of Fault Clearing by A Circuit Breaker In Presence of A Shunt Capacitor Bank," 2008.
14. L. v. d. Sluis and A. L. J. Janssen, "Clearing faults near shunt capacitor banks," *IEEE Transactions on Power Delivery,* vol. 5, no. 3, pp. 1346-1354, 1990, doi: 10.1109/61.57976.
15. "IEEE Guide for the Application of Capacitance Current Switching for AC High-Voltage Circuit Breakers Above 1000 V," *IEEE Std C37.012-2014 (Revision of IEEE Std C37.012-2005),* pp. 1-73, 2014, doi: 10.1109/IEEESTD.2014.6811140.
16. IEC, "High-voltage switchgear and controlgear part 100 high-voltage alternating-current circuit-breakers," *rue de Varembe, Geneva 20, IEC 62271-100,* 2018.
17. A. S. Pabla, *Electric Power Distribution*. McGraw-Hill, 2011.
18. Y. A, B. A, and B. B, "Point on Voltage Wave Switching for Sympathetic Inrush Current Reduction," in *2018 International Conference on Applied Smart Systems (ICASS)*, 24-25 Nov. 2018 2018, pp. 1-4, doi: 10.1109/ICASS.2018.8651972.
19. A. A. Kusuma, P. A. A. Pramana, and B. S. Munir, "Investigation of 150 kV capacitor voltage transformer breakdown during capacitor bank switching," in *2017 7th International Annual Engineering Seminar (InAES)*, 1-2 Aug. 2017 2017, pp. 1-4, doi: 10.1109/INAES.2017.8068570.
20. S. Abdulsalam and W. Xu, "Sequential phase energisation technique for capacitor switching transient reduction," *IET Generation, Transmission & Distribution,* vol. 1, no. 4, pp. 596-602, 2007.
21. MAHFOUD, A. J., & ELLAFI, A. F. (2025). Designing and Implementing a Self-checking Bubble sort Utilizing Dong’s Code Methodology. Bani Waleed University Journal of Humanities and Applied Sciences, 10(3), 701-709.
22. D. F. Miller, "Application guide for shunt capacitors on industrial distribution systems at medium voltage levels," *IEEE Transactions on Industry Applications*, no. 5, pp. 444-459, 2007.
23. F. A. S. Borges, R. A. S. Fernandes, I. N. Silva, and C. B. S. Silva, "Feature Extraction and Power Quality Disturbances Classification Using Smart Meters Signals," *IEEE Transactions on Industrial Informatics,* vol. 12, no. 2, pp. 824-833, 2016, doi: 10.1109/TII.2015.2486379.

24. A. Kalyuzhny, S. Zissu, and D. Shein, "Analytical Study of Voltage Magnification Transients Due to Capacitor Switching," *IEEE Transactions on Power Delivery*, vol. 24, no. 2, pp. 797-805, 2009, doi: 10.1109/TPWRD.2008.2002844.
25. T. A. Bellei, R. P. O. Leary, and E. H. Camm, "Evaluating capacitor-switching devices for preventing nuisance tripping of adjustable-speed drives due to voltage magnification," *IEEE Transactions on Power Delivery*, vol. 11, no. 3, pp. 1373-1378, 1996, doi: 10.1109/61.517494.
26. G. Brunello, Bogdan Kasztenny, and Craig Wester, "Shunt capacitor bank fundamentals and protection," In 2003 Conference for Protective Relay Engineers., April 2003, pp. 1-17.
27. I. Nisja and M. Zoni, "Study of capacitor bank switching transient in distribution network," in *MATEC Web of Conferences*, 2018, vol. 248: EDP Sciences, p. 02004.
28. E. Solorzano and P. Rush, "Application of Load Break Switches for Switching High-Voltage AC Shunt Capacitor Banks," *IEEE Transactions on Power Apparatus and Systems,* no. 4, pp. 1504-1510, 2007.
29. Algheetah, R., & Aldeeb, A. N. (2023). Studying The Quality of Transmitted Signal Via a Wireless and Wired Lines. Bani Waleed University Journal of Humanities and Applied Sciences, 8(3), 293-301.
30. L. Van der Sluis, *Transients in power systems*. Wiley, 2001.
31. D. Durbak *et al.*, "Modeling guidelines for switching transients," *IEEE Modeling and Analysis of System Transients Working Group,* 1998.
32. M. Iizarry-Silvestrini and T. Vélez-Sepúlveda, "Mitigation of back-to-back capacitor switching transients on distribution circuits," *Department of Electrical and Computer Engineering, University of Puerto Rico,* 2006.
33. T. M. Blooming and D. J. Carnovale, "Capacitor application issues," in *Conference record of 2007 annual pulp and paper industry technical conference*, 2007: IEEE, pp. 178-190.
34. F. F. d. Silva, C. L. Bak, U. S. Guomundsdottir, W. Wiechowski, and M. R. Knardrupgard, "Use of a pre-insertion resistor to minimize zero-missing phenomenon and switching overvoltages," in *IEEE Power & Energy Society General Meeting*, 26-30 July 2009, pp. 1-7, doi: 10.1109/PES.2009.5275992.
35. M. S. Javadi, A. Esmaeel Nezhad, P. Siano, M. Shafie-khah, and J. P. S. Catalão, "Shunt capacitor placement in radial distribution networks considering switching transients decision making approach," *International Journal of Electrical Power & Energy Systems,* vol. 92, pp. 167-180, 2017/11/01/ 2017, doi: https://doi.org/10.1016/j.ijepes.2017.05.001.
36. M. Mešter, "Alternative Transient Program-The Powerfull Tool for Power Engineering Simulations," *Acta Electrotechnica et Informatica,* vol. 4, no. 1, pp. 43-46, 2004.

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