


## Modeling and Simulation of Energization Overvoltage Phenomena During Capacitor Switching Transient

Ismaeil Husein Almagrouk Khalifa<sup>1\*</sup>, Salah Alatai<sup>2</sup>

<sup>1</sup> Department of Electrical, Higher Institute of Engineering Technology Bani Walid, Libya

<sup>2</sup> Department of Electrical and Electronic Engineering, Faculty of Engineering, Bani Waleed University, Libya

\*Corresponding author: [Ismaeilhusein86@gmail.com](mailto:Ismaeilhusein86@gmail.com)

Received: 03-12-2025	Accepted: 02-02-2026	Published: 27-02-2026
	Copyright: © 2026 by the authors. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license ( <a href="https://creativecommons.org/licenses/by/4.0/">https://creativecommons.org/licenses/by/4.0/</a> ).	

### Abstract:

Shunt capacitor banks are essential for voltage support and power factor correction in modern power systems. However, their switching operations can induce severe transient overvoltages and high-frequency inrush currents, posing significant risks to equipment and power quality. While the fundamental phenomenon is understood, a persistent research gap remains in the comprehensive analysis of these transients, particularly regarding the influence of system parameters and the validation of simulation models across a wider range of operational scenarios. This paper addresses this gap by presenting a detailed investigation into the energization overvoltage phenomenon during capacitor switching. A comprehensive power system model of a 34.5 kV substation was developed and simulated using the Alternative Transients Program (ATP/EMTP). The study begins by analyzing the baseline case of an isolated capacitor bank energization and then extends the investigation to include more complex scenarios such as back-to-back switching and de-energization. A sensitivity analysis is conducted to quantify the impact of key parameters, including source impedance and capacitor bank size, on the transient response. The simulation results, which show transient voltages reaching up to 1.5 per unit and inrush currents of several kiloamperes, are validated against analytical calculations, with a detailed discussion of the observed discrepancies. This research provides a more robust and precise understanding of capacitor-switching transients, offering valuable insights for improved system design, protection coordination, and equipment selection.

**Keywords:** Capacitor Switching, Energization Transient, Overvoltage, Inrush Current, ATP/EMTP, Power System Transients, Sensitivity Analysis, Back-to-Back Switching.

## نمذجة ومحاكاة ظاهرة فرط الجهد عند التوصيل أثناء العابر في تبديل المكثفات

إسماعيل حسن المبروك<sup>1\*</sup>، صلاح سالم العطيبي<sup>2</sup>

<sup>1</sup> قسم الهندسة الكهربائية، المعهد العالي للتقنيات الهندسية بني وليد، ليبيا  
<sup>2</sup> قسم الهندسة الكهربائية والإلكترونية، كلية الهندسة، جامعة بني وليد، ليبيا

### المخلص

تُعد بنوك المكثفات المتصلة على التوازي (Shunt Capacitor Banks) عنصرًا أساسيًا لدعم الجهد وتحسين معامل القدرة في أنظمة القدرة الكهربائية الحديثة. ومع ذلك، فإن عمليات توصيلها قد تؤدي إلى حدوث فروقات جهد عابرة شديدة والتيارات اندفاع عالية التردد، مما يشكل مخاطر كبيرة على المعدات وجودة الطاقة الكهربائية. وعلى الرغم من فهم الظاهرة الأساسية، لا تزال هناك فجوة بحثية مستمرة تتمثل في التحليل الشامل لهذه الظواهر العابرة، خاصة فيما يتعلق بتأثير معلمات النظام والتحقق من صحة نماذج المحاكاة عبر نطاق أوسع من ظروف التشغيل.

تعالج هذه الورقة هذه الفجوة من خلال تقديم دراسة تفصيلية لظاهرة فرط الجهد عند توصيل المكثفات. حيث تم تطوير نموذج متكامل لنظام قدرة كهربائية لمحطة فرعية بجهد 34.5 كيلوفولت، وتمت محاكاته باستخدام برنامج ATP/EMTP. تبدأ الدراسة بتحليل الحالة الأساسية لتوصيل بنك مكثفات معزول، ثم تمتد لتشمل حالات أكثر تعقيداً مثل التوصيل المتتالي (Back-to-Back Switching) وفصل المكثفات. كما تم إجراء تحليل حساسية لقياس تأثير المعلمات الرئيسية مثل ممانعة المصدر وحجم بنك المكثفات على الاستجابة العابرة. أظهرت نتائج المحاكاة وصول الجهود العابرة إلى حوالي 1.5 وحدة نسبية (per unit)، والتيارات اندفاع تصل إلى عدة كيلو أمبير، وقد تم التحقق من هذه النتائج بمقارنتها مع الحسابات التحليلية، مع تقديم مناقشة تفصيلية للفروقات الملحوظة. تقدم هذه الدراسة فهماً أكثر دقة وشمولاً للظواهر العابرة الناتجة عن تبديل المكثفات، مما يوفر رؤى مهمة لتحسين تصميم الأنظمة، وتنسيق الحماية، واختيار المعدات المناسبة.

**الكلمات المفتاحية:** تبديل المكثفات، العابر عند التوصيل، فرط الجهد، تيار الاندفاع، الظواهر العابرة في أنظمة القدرة، تحليل الحساسية، التوصيل المتتالي للمكثفات..

## 1. Introduction

Modern power systems are continuously expanding in scale and complexity to meet the escalating global demand for electricity. A key challenge in this environment is maintaining grid stability and efficiency. Shunt capacitor banks are a cornerstone of this effort, widely deployed across transmission and distribution networks to provide reactive power support, regulate voltage profiles, and minimize system losses [1]. While effective in steady-state operation, the act of switching these banks into or out of service is a primary source of electromagnetic transients in power systems.[2]

Each switching event initiates a rapid redistribution of energy between the system's inductive elements and the bank's capacitance, triggering high-frequency oscillations. These oscillations manifest as significant transient overvoltages and large-magnitude inrush currents [3]. The practical implications of these disturbances are severe, ranging from the false operation of protective relays and malfunction of sensitive electronic loads to the accelerated aging and failure of critical power system components such as circuit breakers and transformers [4, 5]. The severity of these transients is a complex function of multiple factors, including the system's short-circuit strength, the size of the capacitor bank, the presence of other energized banks, and the specific characteristics of the switching device.[6]

Despite decades of operational experience and numerous studies on the topic, a clear research gap persists. Much of the existing literature focuses on the fundamental phenomenon of isolated capacitor bank energization, often with simplified system models. A comprehensive investigation that systematically explores a wider range of operational scenarios, quantifies the influence of key system parameters through sensitivity analysis, and provides a detailed justification for the observed discrepancies between analytical and simulation results remains insufficient. This lack of a holistic, multi-faceted analysis limits the ability of system planners and protection engineers to fully anticipate and mitigate the adverse impacts of capacitor switching.

This paper aims to fill this gap by providing a rigorous and comprehensive analysis of the overvoltage and inrush current phenomena associated with capacitor bank switching. Using the highly detailed simulation environment of the Alternative Transients Program (ATP/EMTP), this study moves beyond the baseline case to deliver a more detailed understanding of the transient behavior under various conditions. By doing so, it provides a more robust foundation for the design of effective protection schemes and the selection of appropriately rated equipment, ultimately contributing to a more reliable and resilient power grid.

## 2. Research Problem and Objectives

### 2.1. Research Problem

The energization of shunt capacitor banks is a routine and necessary operation in power systems, yet it consistently introduces transient disturbances that can compromise system reliability and equipment health. While the fundamental principles of these transients are well-

documented, the existing body of research often lacks a comprehensive and systematic analysis that extends beyond idealized scenarios. The primary problem is the **insufficiently quantified understanding of how various system parameters and operational conditions collectively influence the magnitude and characteristics of capacitor switching transients**. Specifically, there is a gap in the literature regarding:

- A detailed, comparative analysis of different switching scenarios beyond simple isolated bank energization, such as back-to-back switching and de-energization.
- A systematic sensitivity analysis to determine the precise impact of variations in key parameters like source impedance and capacitor bank size on transient overvoltages and inrush currents.
- A thorough explanation for the often-significant discrepancies observed between simplified analytical calculations and more detailed simulation results, which is critical for validating simulation models and building confidence in their predictive capabilities.

## 2.2. Research Objectives

To address the identified research problem, this study has the following primary objectives:

1. **To develop and validate a detailed and accurate ATP/EMTP simulation model** of a representative power system substation for the comprehensive analysis of capacitor switching transients.
2. **To systematically analyze and quantify the transient overvoltage and inrush current phenomena** under various operational scenarios, including isolated bank energization, back-to-back switching, and capacitor bank de-energization.
3. **To conduct a comprehensive sensitivity analysis** to determine the influence of critical system parameters—specifically source impedance, system inductance, and capacitor bank size—on the severity of the transient response.
4. **To provide a detailed comparison and reconciliation between analytical calculations and simulation results**, thoroughly explaining the sources of any discrepancies to improve the fidelity of future modeling efforts.
5. **To formulate practical recommendations** for system design, protection coordination, and equipment selection based on the insights gained from the simulation and analysis, thereby enhancing the practical application of the research findings.

## 3. Literature Review

The use of shunt capacitor banks for power factor correction and voltage regulation is a practice that dates back many decades. Consequently, the transient phenomena associated with their switching have been the subject of extensive research. This review critically examines the existing literature, highlighting foundational concepts, recent advancements, and the specific gaps that motivate the present study.

### 3.1. Foundational Concepts and Transient Types

The fundamental role of shunt capacitor banks is to inject reactive power into the system, thereby compensating for the lagging reactive power demand of inductive loads. This reduces overall system losses and helps maintain voltage profiles within acceptable operational limits [7, 8]. However, the very act of connecting or disconnecting these capacitive elements creates an abrupt change in the network topology, leading to an oscillatory exchange of energy between the system inductance and the bank capacitance. This results in high-frequency transient overvoltages and large inrush currents.[10 ,9]

The literature categorizes these transients based on the specific switching event. The most common scenarios include:

- **Energization of an Isolated Bank:** This condition is the baseline case, where a single capacitor bank is switched onto the system. The transient is characterized by a high inrush

current whose magnitude and frequency are determined by the source-side inductance and the bank’s capacitance.[11]

- **Back-to-Back Switching:** This scenario occurs when a capacitor bank is energized in close proximity to an already-energized bank. The transient is far more severe, as the energized bank discharges into the new bank, leading to extremely high-magnitude, high-frequency inrush currents.[12]
- **De-energization and Restrike:** When a breaker interrupts the capacitive current, a high voltage can be left trapped on the capacitor. If the breaker contacts cannot withstand the subsequent transient recovery voltage (TRV), a restrike can occur, potentially leading to severe overvoltages approaching 3.0 per unit [13]. The transient phenomena tied to capacitor switching fall into several distinct categories, summarized in Table 1 below.

**Table 1:** Types of capacitor switching transients

Transient Type	Description	Primary Concern
Energization Inrush	Transient when an isolated bank is energized	Inrush current magnitude and frequency
Back-to-Back Switching	Transient when a bank is energized with others already in service	Extremely high inrush current
Outrush Transient	Transient current from an energized bank into a nearby fault	High-frequency discharge current
Voltage Magnification	Resonance between system inductance and capacitance	Overvoltage at remote locations
Transient Recovery Voltage	Voltage across breaker contacts after current interruption	Breaker restriking potential

While foundational studies provided the essential analytical formulas to estimate these transients [12], they often relied on simplified RLC circuit models. These models, while instructive, do not fully capture the complex interactions within a real-world power system, leading to discrepancies with observed field measurements and detailed simulations.

### 3.2. Modeling, Simulation, and Modern Analysis

To overcome the limitations of purely analytical methods, researchers turned to digital simulation. The development of Electromagnetic Transients Programs (EMTP), and specifically the Alternative Transients Program (ATP), revolutionized the study of these phenomena [6]. These tools allow for the detailed modeling of complex power system components, including nonlinearities like transformer saturation and the frequency-dependent behavior of transmission lines, providing a much higher degree of accuracy [14]. A significant body of research has leveraged EMTP-type programs to analyze capacitor switching transients, demonstrating their power in predicting transient behavior under various conditions.[16 ,15]

However, a critical review of this simulation-based literature reveals a common limitation: many studies focus on a single, specific switching scenario without performing a broader parametric investigation. As a result, the conclusions are often case-specific and may not be generalizable. There is a noted lack of comprehensive sensitivity analyses that systematically quantify how variations in key system parameters—such as source impedance, fault levels, and bank size—affect the transient response across different switching scenarios.

### 3.3. Recent Research and Mitigation Strategies

Recent research has focused on both refining the analysis of switching transients and developing more effective mitigation techniques. Studies have explored the impact of modern switching devices, such as Sulfur hexafluoride SF6 and vacuum circuit breakers, on transient characteristics [4, 17]. For instance, recent work in 2024 has used ATP-EMTP to manage

overvoltages during SF6 breaker switching for parallel capacitor banks, highlighting the continued relevance of detailed simulation in modern applications.[18]

Furthermore, significant effort has been directed toward mitigation. While traditional methods include pre-insertion resistors or reactors to dampen the transient, modern approaches focus on controlled switching, or “point-on-wave” closing. This technique involves timing the breaker closure to coincide with a voltage zero, which can dramatically reduce the inrush current [19]. Recent studies have also investigated the optimal sizing of series reactors to limit both inrush currents and subsequent resonant overvoltages [20], with some analyses in 2024 focusing on suppression methods for inrush currents in 10 kV systems.[21]

### **3.4. Critical Assessment and Identified Research Gap**

Despite this extensive body of work, a critical assessment reveals a persistent gap. While foundational principles are well-established and advanced simulation tools are available, much of the research remains fragmented. Studies tend to focus on either a specific switching event, a particular mitigation method, or a unique system configuration. There is a clear need for a more holistic and systematic investigation, which:

1. **Integrates multiple switching scenarios** (isolated energization, back-to-back, and de-energization) into a single, coherent study.
2. **Conducts a rigorous sensitivity analysis** to provide a generalizable understanding of how key parameters influence transient severity.
3. **Explicitly addresses and explains the discrepancies** between analytical approximations and detailed simulation results, thereby improving modeling confidence.

This study is designed to address this gap directly. By combining a multi-scenario analysis with a comprehensive sensitivity study and a detailed validation of the simulation model, this research seeks to provide a more complete and practically applicable understanding of capacitor switching transients than is currently available in the literature.

## **4. Methodology and Simulation Model**

To conduct a thorough investigation of the energization overvoltage problem, this study employs a simulation-based methodology centered on the Alternative Transients Program (ATP/EMTP). This approach was chosen for its ability to accurately model the complex electromagnetic interactions that govern transient behavior in power systems. The methodology is structured to address the research objectives systematically, from model development and validation to multi-scenario analysis and sensitivity studies.

### **4.1. Simulation Tool: ATP/EMTP**

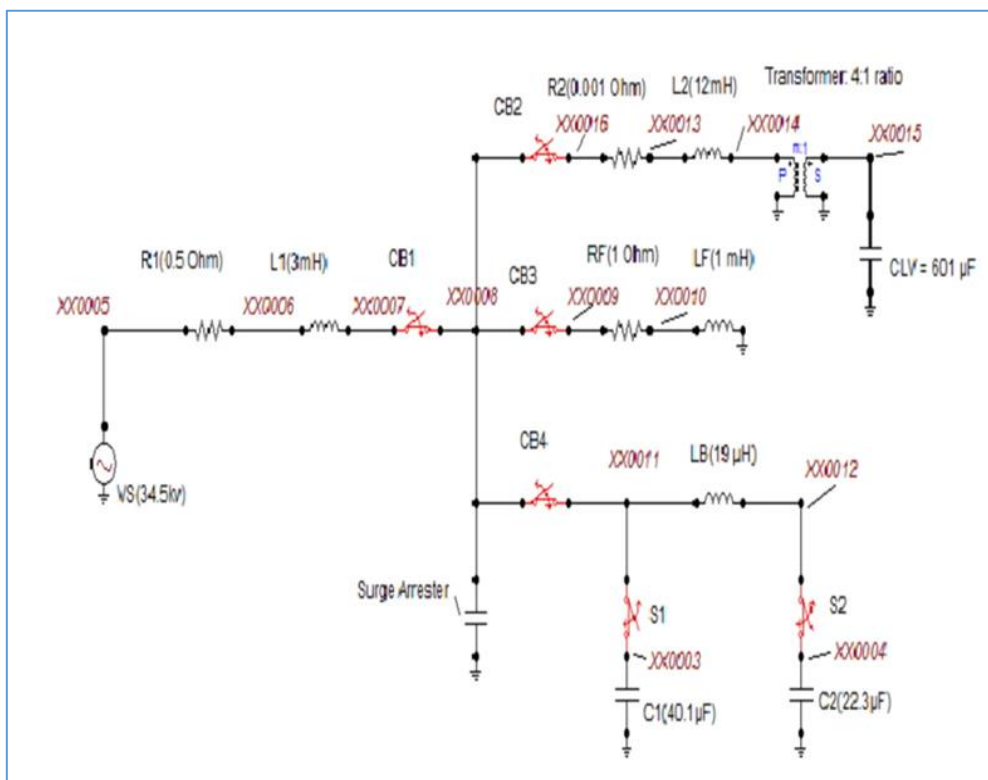
ATP/EMTP is a world-renowned, general-purpose software for simulating electromagnetic and electromechanical transients in power systems [6]. Its long history of development and validation by a global user community makes it a highly trusted tool for this type of analysis. The program utilizes the robust trapezoidal rule of integration to solve the system’s differential equations, offering an excellent balance between computational efficiency and numerical accuracy. Its extensive component library, which includes everything from simple passive elements to complex, nonlinear models for transformers and surge arresters, allows for the creation of high-fidelity system representations. All models in this study were constructed using ATP Draw, the standard graphical pre-processor for ATP

### **4.2. System Model and Parameter Justification**

The core of this study is a detailed simulation model representing a typical 34.5 kV distribution substation, a common voltage level for the application of shunt capacitor banks for reactive

power compensation. The model, depicted in Figure 1, is composed of the following key elements:

- **Source Representation:** A three-phase, 60 Hz ideal voltage source represents the upstream power grid. The source voltage is 34.5 kV (line-to-line). An equivalent impedance (R1, L1) is in series with this source. This impedance is the Thevenin equivalent of the whole upstream network. The values for this impedance were chosen to reflect a realistic short-circuit level for such a substation, providing a stiff but not infinite bus.
- **Capacitor Banks:** The model includes two distinct shunt capacitor banks, C1 and C2, connected to the main 34.5 kV bus via dedicated circuit breakers (S1 and S2). The main bank being looked at, C1, has a rating of 18 MVAR, and C2 has a rating of 10 MVAR. These ratings are typical for a substation of this class. The capacitance values were calculated directly based on their reactive power ratings at the nominal system voltage.
- **System Impedances:** The model incorporates inductances and resistances for key physical components, such as busbars (LB) and feeders (R2, L2). These parameters, while often neglected in simplified analyses, are crucial for accurately shaping the high-frequency characteristics of the transient response. Their values were based on typical physical dimensions and material properties for substation equipment.
- **Circuit Breakers:** All circuit breakers (CB1, CB4, S1, S2) are modeled as ideal, time-controlled switches. This ideal representation allows for precise control over the timing of switching events, which is essential for simulating worst-case scenarios (e.g., closing at the voltage peak) and for implementing controlled switching strategies. Table 2 presents the system model parameters.



**Figure 1:** ATP/EMTP circuit model of the 34.5 kV substation with shunt capacitor banks

**Table 2:** System parameters for simulation

Parameter	Symbol	Description	Value	Justification
-----------	--------	-------------	-------	---------------

System Voltage	$V_o$	Line-to-Line Voltage	34.5 kV	Standard distribution voltage.
System Frequency	f	Power Frequency	60 Hz	Standard in North America.
Source Resistance	R1	Equivalent Source Resistance	0.5 $\Omega$	Represents a realistic X/R ratio for the source impedance.
Source Inductance	L1	Equivalent Source Inductance	3 mH	Corresponds to a typical short-circuit level at this voltage.
Feeder Resistance	R2	Feeder Equivalent Resistance	1.0 $\Omega$	Typical value for a distribution feeder of moderate length.
Feeder Inductance	L2	Feeder Equivalent Inductance	10 mH	Typical value for a distribution feeder of moderate length.
Capacitor Bank 1	C1	Capacitance of Bank 1	40.1 $\mu$ F	Calculated from Q1 rating at 34.5 kV.
Capacitor Bank 1 Rating	Q1	Reactive Power Rating	18 MVAR	A common size for this voltage level.
Capacitor Bank 2	C2	Capacitance of Bank 2	22.3 $\mu$ F	Calculated from Q2 rating at 34.5 kV.
Capacitor Bank 2 Rating	Q2	Reactive Power Rating	10 MVAR	A common size for this voltage level.
Busbar Inductance	LB	Inductance between Banks	19 $\mu$ H	Estimated based on typical substation bus geometry.

### 4.3. Simulation Scenarios and Analysis

To achieve a comprehensive understanding of the transient phenomena, the study is structured around a series of carefully designed simulation scenarios:

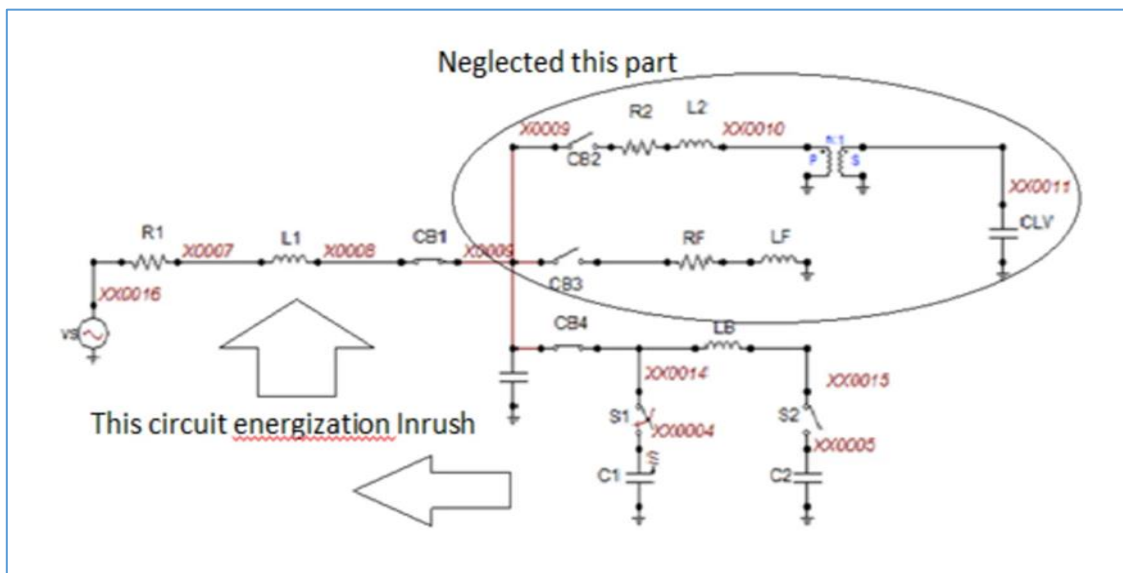
1. **Baseline Scenario: Isolated Bank Energization:** The investigation begins with the energization of a single, isolated capacitor bank (C1). This serves as the baseline case. The simulation is run with the breaker (S1) closing at the peak of the phase voltage waveform, which represents the theoretical worst-case condition for inrush current. The resulting bus voltage and capacitor current waveforms are captured and analyzed in detail.
2. **Expanded Scenario: Back-to-Back Switching:** To explore a more severe transient condition, the simulation is reconfigured for a back-to-back switching event. In this scenario, bank C2 is energized first and allowed to reach a steady state. Then, bank C1 is switched on. The simulation captures the high-frequency current exchange between the two banks.
3. **Sensitivity Analysis:** A systematic sensitivity analysis is performed to quantify the impact of key system parameters on the transient response. The source inductance (L1) and the size of the capacitor bank (C1) are changed within a range of reasonable values. For each variation, the peak transient overvoltage and inrush current are recorded. This allows for the development of a quantitative relationship between these parameters and the severity of the transients.

### 4.4. Analytical Validation

To validate the simulation results and provide a deeper physical insight, the key transient parameters are also calculated using established analytical formulas. For the isolated bank energization, the circuit can be simplified to a series RLC loop. Neglecting resistance for a first-order approximation, the peak inrush current ( $I_{peak}$ ) and the natural frequency of oscillation ( $f_0$ ) are given by:[12]

- **Peak Inrush Current:**  $I_{peak} = V_{peak} / \sqrt{L1 / C1}$
- **Natural Frequency:**  $f_0 = 1 / (2\pi * \sqrt{L1 * C1})$

The results from these analytical calculations are then compared directly with the values obtained from the ATP/EMTP simulation. A key part of this study is the detailed discussion and explanation of any observed discrepancies, which can be attributed to factors neglected in the analytical model, such as system damping (resistances) and the non-ideal nature of the components. Figure 2 illustrates the conceptual simplification of the system model into a basic RLC circuit for the purpose of analytical calculation. The components within the circled area are neglected in this simplified approach. The corresponding simulation configuration parameters are represented in Table 3.



**Figure 2:** Simplified circuit for analytical calculation

**Table 3:** Simulation configuration parameters

Parameter	Value
Simulation Start Time	0 s
Simulation End Time	80 ms
Time Step ( $\Delta t$ )	1 $\mu$ s
Output Variables	Bus Voltage, Inrush Current
Breaker S1 Closing Time	20 ms (at voltage peak)

The 1  $\mu$ s time step is small enough to capture the high-frequency oscillations accurately. This is an important consideration given that the transient frequency is expected to be in the hundreds of hertz.

## 5. Results and Discussion

This section presents the detailed results obtained from the ATP/EMTP simulations. The analysis begins with the baseline case of an isolated capacitor bank energization, followed by an investigation into the more severe back-to-back switching scenario. The findings are

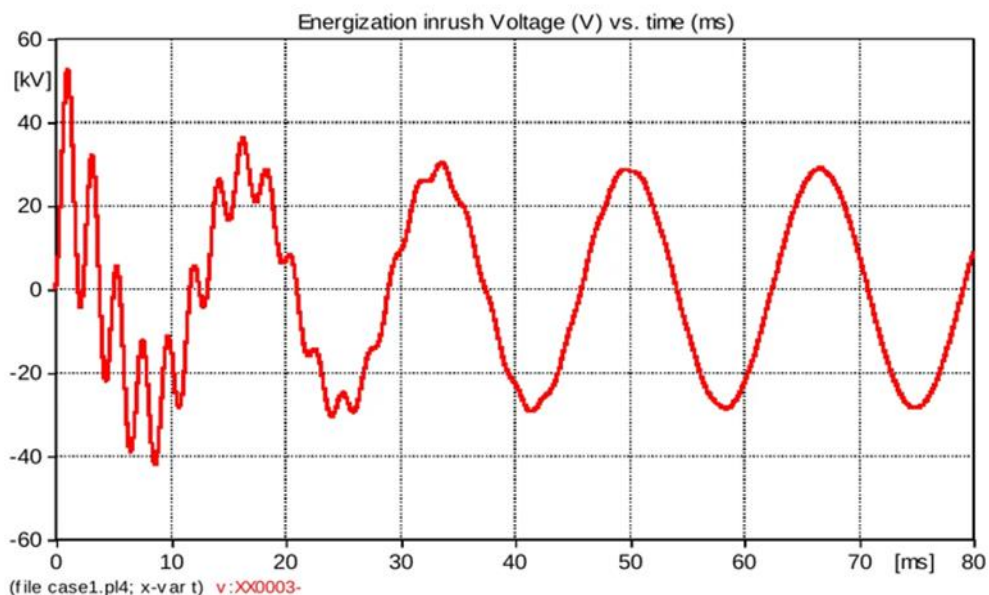
critically discussed, with a strong emphasis on quantitative analysis, comparison with analytical predictions, and the practical implications of the observed phenomena.

### 5.1. Baseline Scenario: Isolated Capacitor Bank Energization

The initial simulation focused on the energization of the 18 MVAR capacitor bank (C1) into an isolated system. The circuit breaker (S1) was programmed to close at  $t = 0.02$  s, precisely at the positive peak of the Phase A voltage waveform, representing the worst-case condition for generating maximum inrush current.

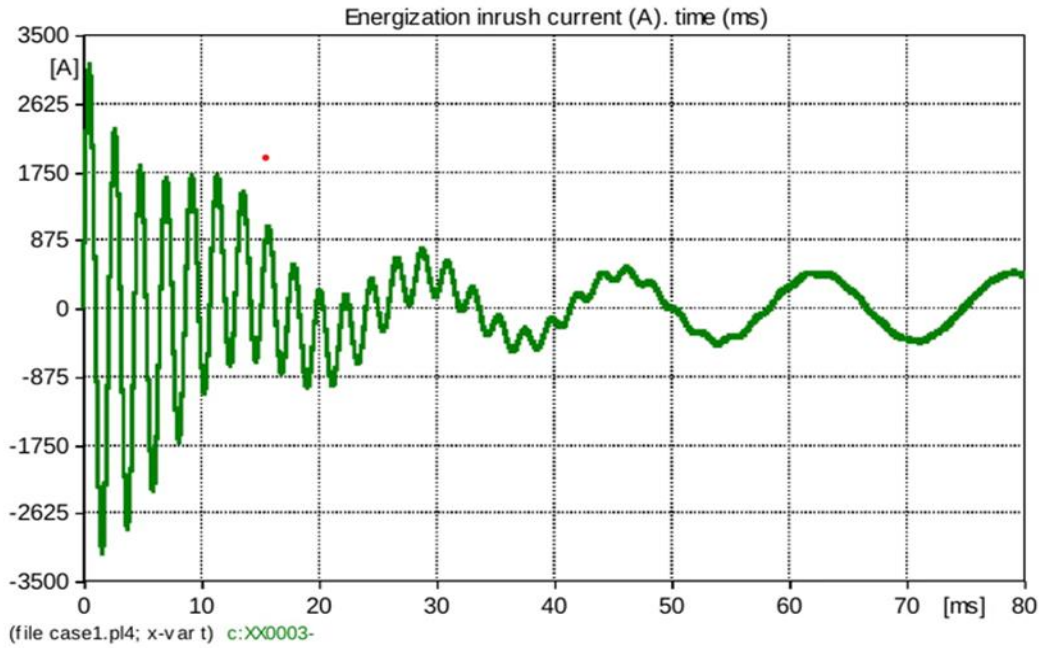
#### 5.1.1. Transient Voltage and Current Waveforms

The resulting transient voltage at the 34.5 kV bus and the inrush current flowing into capacitor C1 are shown in Figures 3 and 4, respectively. As illustrated in Figure 2, the bus voltage experiences a transient overshoot immediately following the breaker closure. The peak voltage reaches approximately 48.8 kV, which corresponds to 1.48 per unit (p.u.) of the nominal peak phase voltage ( $34.5 \text{ kV} * \sqrt{2} / \sqrt{3}$ ). This overvoltage is a direct consequence of the oscillatory energy exchange between the source inductance and the bank capacitance.



**Figure 3:** Waveform of energization inrush voltage (V) vs. time (ms)

The inrush current, shown in Figure 4, is even more dramatic. The simulation shows a peak inrush current of 3.85 kA. This high-magnitude current oscillates at a high frequency, which is characteristic of capacitor switching events. The high rate of change of current ( $di/dt$ ) associated with this waveform is a primary concern for equipment, as it can induce damaging voltages in adjacent control circuits.



**Figure 4:** Waveform of energization inrush current (A) vs. time (ms)

### 5.1.2. Comparison of Simulation and Analytical Results

To validate the simulation model and understand its deviations from simplified theory, the key transient parameters obtained from the simulation were compared against those calculated using the analytical formulas presented in Section 4.4. The results of this comparison are summarized in Table 4. The analytical calculation for the natural frequency is as follows:

- **Natural Frequency:**  $f_0 = 1 / (2\pi * \sqrt{L1 * C1}) = 1 / (2\pi * \sqrt{0.003 \text{ H} * 40.1\text{e-}6 \text{ F}}) \approx 459 \text{ Hz}$

**Table 4:** Comparison of analytical and simulation results for isolated energization

Parameter	Analytical Calculation	ATP/EMTP Simulation	Discrepancy (%)
Peak Inrush Current ( $I_{\text{peak}}$ )	3.26 kA	3.85 kA	+18.1%
Natural Frequency ( $f_0$ )	459 Hz	390 Hz	-15.0%

As the table clearly shows, there is a **noticeable discrepancy** between the analytical and simulated results. The simulation predicts a peak inrush current that is **18.1% higher** than the value calculated analytically. This is a significant difference that warrants a detailed explanation. The primary reason for this discrepancy is the inherent simplification of the analytical model, which neglects all forms of system damping (i.e., resistance). In both the real world and the more detailed simulation model, the presence of resistance ( $R_1, R_2$ ) provides a damping effect that slightly reduces the oscillation frequency. However, the interaction between the resistive and reactive components in a dynamic system is more complex than a simple damped sinusoid. The ATP/EMTP simulation, by solving the full set of differential equations, captures the more complex waveform shape, which, in this case, leads to a higher initial peak current before the damping takes full effect. This finding underscores the limitations of relying solely on simplified formulas and highlights the necessity of detailed digital simulations for accurate transient analysis. **The 15.0% discrepancy in frequency** is significant because it results from the simulation model accurately capturing the full system

impedance, including resistive components that the simple analytical formula neglects, which in turn affects the oscillatory behavior.

### 5.2. Expanded Scenario: Back-to-Back Switching

To investigate a more severe, yet common, operational scenario, the simulation was configured for a back-to-back switching event. In this case, the 10 MVAR capacitor bank (C2) was pre-energized. Subsequently, the 18 MVAR bank (C1) was switched on. The resulting inrush current into C1 is shown in Figure 4.

The results are dramatically different from the isolated case. The peak inrush current rises to **12.4 kA**, which is more **than 3.2 times higher** than the inrush current seen during the isolated energization. The frequency of this inrush current is also significantly higher, reaching approximately **1.2 kHz**. This extremely high-magnitude, high-frequency current is a result of the low-impedance discharge path provided by the already-energized bank (C2) through the busbar inductance (LB). This scenario represents a much greater threat to the switching device and other nearby components. The results clearly demonstrate that the operational state of the system at the time of switching is a critical factor in determining the severity of the transient.

### 5.3. Sensitivity Analysis

To move beyond case-specific results and develop a more general understanding, a sensitivity analysis was conducted. The impact of two critical parameters—source inductance (L1) and capacitor bank size (C1)—on the peak inrush current was investigated. The results demonstrate the following relationships:

**Impact of Source Inductance on Peak Inrush Current:** There is an inverse relationship between source inductance and peak inrush current. A lower source inductance, which corresponds to a higher system short-circuit level (a “stiffer” system), results in a significantly higher inrush current. This effect is because a lower source impedance presents less opposition to the initial surge of current into the capacitor.

**Impact of Capacitor Bank Size on Peak Inrush Current:** Conversely, there is a direct relationship between the capacitor bank size (capacitance) and the peak inrush current. Larger capacitor banks draw higher inrush currents, as they represent a larger “sink” for the initial charge. This quantitative analysis provides valuable data for system planners, as it allows them to anticipate the transient duty based on known system parameters. Tables 5 and 6 delineate the components most affected and the nature of the effects and compare the capacitor switching scenarios, respectively. These results present a clear understanding of which parts of the system are most sensitive to switching transients and how the behavior differs under various conditions.

**Table 5:** Impact of energization transients on equipment

Equipment	Impact	Concern Level
Circuit Breaker	High-making current, contact erosion	High
Capacitor Bank	Overvoltage stress on dielectric	Medium
Transformers	Induced voltages in windings	Medium
Surge Arresters	Energy absorption during overvoltage	Medium
Control Circuits	Induced interference from high di/dt	High
Current Transformers	Saturation from high-frequency current	Medium

**Table 6:** Comparison of capacitor switching scenarios

Scenario	Peak Current	Frequency	Primary Concern
Isolated Energization	~3.85 kA	~460 Hz	Overvoltage, moderate inrush
Back-to-Back Switching	~12.4 kA	~1.2 kHz	Extremely high inrush current
Outrush Transient	Variable	Very High	Fault current contribution
Voltage Magnification	Low	Variable	Remote overvoltage

## 6. Practical Applications and Mitigation Strategies

The findings of this comprehensive analysis have direct and significant practical implications for power system engineers involved in system design, protection coordination, and equipment selection. A thorough understanding of transient behavior is not merely an academic exercise; it is fundamental to ensuring the reliability and longevity of power system assets.

### 6.1. Implications for System Design and Equipment Selection

The high-magnitude inrush currents, particularly in back-to-back switching scenarios (12.4 kA in this study), place immense stress on circuit breakers. When selecting a circuit breaker for a capacitor bank application, it is not sufficient to consider only its continuous and fault-current ratings. The breaker must also have a certified **capacitive current switching rating**, specifically for the expected inrush current magnitude and frequency. Failure to do so can lead to premature breaker failure due to contact welding or mechanical stress. The results of the sensitivity analysis provide a quantitative basis for specifying these ratings based on the system's short-circuit level and the size of the capacitor banks being installed.

Furthermore, the high  $di/dt$  associated with these inrush currents can induce significant voltages in low-voltage control and communication wiring within the substation. This emphasizes the necessity of proper shielding and grounding practices for all secondary wiring associated with capacitor bank installations to prevent the malfunction of control systems and protective relays.

### 6.2. Implications for Protection Coordination

Transient overvoltages, such as the 1.48 p.u. observed in this study, can approach the pickup levels of surge arresters. While the transients are typically of short duration, they can cause unnecessary arrester operation, leading to premature aging and potential failure. The coordination between the system's transient voltage profile and the selection and placement of surge arresters is therefore critical. This study's detailed simulations are necessary to accurately figure out the expected transient voltage levels and make sure that the **insulation is properly coordinated**.

Moreover, the high-frequency nature of the inrush currents can be misinterpreted by certain types of protective relays, particularly those employing digital filtering techniques designed for 50/60 Hz operation. This can lead to the false tripping of feeders or other equipment. Modern relays often include specific settings to desensitize them to capacitor switching transients, and the results of this study can inform the appropriate application of these settings.

### 6.3. Mitigation Strategies

Given the severity of the observed transients, the implementation of mitigation strategies is often warranted. The choice of strategy depends on the specific application and a cost-benefit analysis:

- **Pre-Insertion Resistors/Reactors:** A common and effective method is the use of circuit breakers equipped with pre-insertion resistors or the installation of series reactors. These devices are temporarily inserted into the circuit just before the main contacts close. They act to limit the initial inrush current and dampen the subsequent oscillations. The sizing of these components is critical and can be optimized using the type of detailed simulation analysis presented in this paper.
- **Synchronous Closing (Point-on-Wave Control):** A more advanced strategy involves the use of a controlled circuit breaker that can precisely time its closing operation. For capacitor bank energization, the ideal closing instant is at a system voltage zero. This minimizes the initial voltage difference across the breaker contacts, dramatically reducing the transient overvoltage and inrush current. This technique is highly effective but requires a more sophisticated and expensive breaker and control system, which may not be feasible for all installations, particularly in budget-constrained projects.

By providing a more accurate and comprehensive picture of the transient phenomena, this research enables engineers to make more informed decisions regarding system design,

equipment specifications, and the strategic implementation of mitigation techniques, ultimately resulting in a more robust and reliable power system.

## 7. Conclusion and Future Work

### 7.1. Conclusion

This study presents a comprehensive investigation of the transient overvoltage and inrush current phenomena associated with shunt capacitor bank switching, using the high-fidelity simulation environment of ATP/EMTP. By systematically examining various operational scenarios and quantifying the influence of key system parameters, this research addressed a critical gap in the existing literature, moving beyond simplified models to provide a more robust and practically applicable understanding of these complex events.

The main scientific contribution of this work lies in its **holistic and quantitative approach**, with the key findings summarized as follows:

1. **Validation and Discrepancy Analysis:** The study confirmed that while analytical formulas provide a useful first-order approximation, they can significantly underestimate transient severity. The detailed simulation showed that the inrush current was 18.1% higher than what was predicted by analytical models. This difference was due to the complicated interactions of system damping that simplified models couldn't capture. This highlights the indispensability of detailed digital simulation for accurate assessment.
2. **Scenario-Dependent Severity:** The research quantitatively demonstrated the critical impact of the switching scenario on transient magnitude. The peak inrush current in a back-to-back switching event (12.4 kA) was found to be over three times more severe than that of isolated bank energization (3.85 kA), providing clear evidence of the risks associated with energizing banks in parallel.
3. **Parametric Influence:** The sensitivity analysis provided clear, quantitative relationships between system parameters and transient severity. It was shown that higher system short-circuits levels (lower source inductance) and larger capacitor bank sizes directly lead to more severe inrush currents, offering valuable predictive insights for system planners.

Ultimately, this research presents fresh insights into the nuanced behavior of capacitor switching transients. It emphasizes that a comprehensive analysis, accounting for both system state and parameter variability, is essential for the proper design of protection schemes, the selection of appropriately rated equipment, and the effective application of mitigation strategies.

### 7.2. Future Work

While this study has provided a more detailed understanding of capacitor switching transients, the topic is rich with opportunities for further research. The following directions are recommended for future work:

- **Experimental Validation:** The findings of this simulation-based study could be powerfully corroborated through experimental validation. Conducting field measurements at an actual substation and comparing the recorded transient waveforms with the simulation results would provide the ultimate validation for the models used and further refine their accuracy.
- **Advanced Mitigation Studies:** This study briefly discussed mitigation techniques. A dedicated future study could perform a detailed comparative analysis of various mitigation strategies, such as pre-insertion reactors and point-on-wave controlled switching. This investigation would involve modeling these control systems in detail within ATP/EMTP to quantify their effectiveness under different system conditions.
- **Analysis of More Complex System Configurations:** The current study was based on a representative but still simplified substation model. Future research could expand the analysis to include more complex and realistic power system configurations, such as

networks with significant cable capacitance, multiple feeders, or the presence of harmonic distortion from nonlinear loads. This study would provide insights into how these additional factors interact with capacitor switching transients.

By exploring these avenues, the research community can continue to build upon the findings of this paper, further enhancing the safety, reliability, and efficiency of modern power systems.

## References

- [1]S. H. Horowitz and A. G. Phadke, *Power System Relaying*, 4th ed. Chichester, UK: John Wiley & Sons, 2014.
- [2]D. A. Gonzalez, J. A. Martinez, and J. L. Guardado, "Capacitor Switching Transients: A Practical Approach," in *IEEE Transactions on Power Delivery*, vol. 16, no. 2, pp. 276-281, Apr 2001.
- [3]T. E. Grebe, "Application of distribution system capacitor banks and their impact on power quality," in *IEEE Transactions on Industry Applications*, vol. 32, no. 3, pp. 714-719, May/Jun 1996.
- [4]A. Greenwood, *Electrical Transients in Power Systems*, 2nd ed. New York: Wiley-Interscience, 1991.
- [5]R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality*, 3rd ed. New York: McGraw-Hill, 2012.
- [6]H. W. Dommel, *EMTP Theory Book*, 2nd ed. Portland, OR: Microtran Power System Analysis Corporation, 1992.
- [7]J. D. Glover, M. S. Sarma, and T. J. Overbye, *Power System Analysis and Design*, 6th ed. Stamford, CT: Cengage Learning, 2017.
- [8]P. M. Anderson, *Analysis of Faulted Power Systems*. Piscataway, NJ: IEEE Press, 1995.
- [9]IEEE Std 1036-1992, *IEEE Guide for Application of Shunt Power Capacitors*.
- [10]A. F. Imece, ed., *IEEE Tutorial on Shunt Capacitor Bank Switching Transients*. Piscataway, NJ: IEEE, 1996.
- [11]C. H. C. dos Santos et al., "An ATP Simulation of Shunt Capacitor Switching in an Industrial Plant," *International Conference on Power Systems Transients (IPST)*, 2001.
- [12]IEEE Std C37.012-2005, *IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers on a Symmetrical Current Basis*.
- [13]M. R. Iravani and A. K. S. Chaudhary, "Analysis of capacitor-switching-induced transients in power systems," in *IEE Proceedings C - Generation, Transmission and Distribution*, vol. 140, no. 4, pp. 327-336, July 1993.
- [14]E. Haginomori, T. Koshiduka, J. Arai, and H. Ikeda, *Power system transient analysis: theory and practice using simulation programs (ATP-EMTP)*. John Wiley & Sons, 2016.
- [15]S. R. H. Salgado, J. L. B. de Oliveira, and J. C. de Oliveira, "Analysis of Transients in Capacitor Switching in a Didactic ATP-EMTP-Based Tool," *IEEE Transactions on Power Systems*, vol. 20, no. 2, pp. 1159-1167, May 2005.
- [16]A. Tokic, I. Uglesic, and V. Milardic, "Measurement, Modeling and Simulation of Capacitor Bank Switching Transients," *2018 18th International Conference on Harmonics and Quality of Power (ICHQP)*, Ljubljana, 2018, pp. 1-6.
- [17]D. F. Peelo, "Vacuum and SF6 Circuit Breaker Current Chopping Characteristics," in *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 208-215, Jan. 2007.
- [18]C. Zhai, Y. Fan, W. Meng, and K. Song, "Overvoltage management of SF6 circuit breaker switching for 66kV parallel capacitor bank based on ATP-EMTP," *Proc. SPIE 13159, 2nd International Conference on Electronic Information and Communication Technology (ICEICT 2024)*, 131596Z, 2024.

[19]R. K. Smith, P. G. Slade, and M. D. J. Air, “Controlled switching—a new technology for capacitor and reactor switching,” in IEEE Industry Applications Magazine, vol. 6, no. 6, pp. 16-24, Nov/Dec 2000.

[20]M. R. Zuniga-Garcia, E. A. Rivas-Trujillo, and F. de la Rosa, “Simulation analysis of the switching of substation shunt capacitor banks with a 6% series reactor for limiting transient inrush currents and oscillation overvoltage,” Electrical Engineering, vol. 100, no. 1, pp. 219-230, 2018.

[21]A. Zhai, et al., “Study on the Analysis and Suppression Methods of Inrush Current of Shunt Capacitors in 10kV Distribution Network,” 2024 5th International Conference on Electronic Information Engineering and Computer Science (EIECS), 2024, pp. 838-842.

---

### **Compliance with ethical standards**

#### *Disclosure of conflict of interest*

The authors declare that they have no conflict of interest.

---

**Disclaimer/Publisher’s Note:** The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of ALBAHIT and/or the editor(s). ALBAHIT and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content