MEDIUM-VOLTAGE CAPACITOR BANK SWITCHING PEAK INRUSH CURRENT AND DEVICE RATING EVALUATION

VarStec Power Solutions
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Abstract - Capacitor bank switching is a routine operation that can impose severe transient current duty on medium-voltage switching devices. Single-bank energization is usually limited by source inductance, but back-to-back energization can produce high peak currents at kilohertz frequencies as energized capacitor stages discharge into an uncharged stage. This paper reviews the distinction between single-bank and back-to-back switching, the calculation of peak inrush current and natural frequency, and the application of IEEE C37 series standards to capacitor switches, circuit breakers, and legacy oil breakers. Mitigation options including transient limiting inductors, point-on-wave switching, pre-insertion resistors, and harmonic filter reactors are discussed.

Index Terms - capacitor bank switching, inrush current, back-to-back switching, transient limiting inductor, point-on-wave switching, capacitor switch, circuit breaker, IEEE C37.012.

I. INTRODUCTION

While shunt capacitor banks are essential for maintaining voltage stability and power factor on modern electrical grids, switching them on and off represents one of the most severe routine transient events a power system has to endure. When an isolated capacitor bank is energized, a high-frequency, high-magnitude charging current, known as an inrush current, flows into the capacitor as it attempts to equalize the system capacitor voltage with the system voltage. For a single capacitor bank, this inrush current is limited by the system's source inductance and rarely exceeds 20 times the bank's rated current.

However, the transient current stresses become significantly more severe during "back-to-back" switching, which occurs when a capacitor stage is energized in close proximity to a previously energized stage. Under these conditions, the inrush current is supplied primarily by the already-energized capacitors discharging into the uncharged bank. Because the limiting inductance in this local loop is strictly the short buswork and connections between the two capacitor banks rather than the much larger system source inductance, the resulting inrush current reaches much higher amplitudes and natural frequencies than those of an isolated bank. This high-frequency release of energy places immense stress on the switching device.

Ensuring that a switching device can safely close into (make) these severe capacitive transient currents without sustaining contact damage is critical, but evaluating that capability is not a one-size-fits-all calculation. The evaluation method depends heavily on the specific technology of the device and the standards that govern it. For example, modern vacuum and SF6 circuit breakers are governed by IEEE Std C37.04-2018 and IEEE Std C37.012-2022, which focus on peak "close and latch" capabilities and assign specific restrike performance classes (C0, C1, and C2). Meanwhile, dedicated vacuum capacitor switches are evaluated under IEEE Std C37.66-2021, which explicitly removes upper frequency limits entirely for non-di/dt sensitive devices, provided the peak inrush magnitude is respected. Conversely, older legacy oil-filled breakers require entirely different, highly restrictive evaluations because the hydraulic shock waves generated by high-frequency transients can physically shatter their interrupters.

The purpose of this VarStec Engineering Brief, and the accompanying VarStec Capacitor Bank Peak Inrush Analysis Tool, is to present the details and complexity around this subject matter, helping engineers confidently navigate the varied standards to ensure safe, compliant, and optimized capacitor bank designs.

II. WHY IT MATTERS

Even a properly designed capacitor bank will become unreliable and potentially hazardous if it is paired with an inadequately rated switching device, whether a circuit breaker, contactor, or capacitor switch. VarStec's field experience and industry testing have shown that equipment failure often begins with improper energization. When the transient inrush current exceeds the capabilities of the switching device, the intense heat and high rate-of-change of current (di/dt) can cause micro-welding, pitting, or severe erosion of the vacuum or SF6 contacts as they close. While the device may survive the initial closure, this hidden contact damage becomes a critical liability during the subsequent de-energization (opening) cycle.

When the damaged contacts attempt to open and interrupt the capacitive current, they often fail to withstand the severe transient recovery voltage that appears across the gap, leading to a restrike. A restrike forces the system voltage to escalate rapidly, often doubling or quadrupling the normal system voltage. These extreme overvoltages can lead to catastrophic consequences, including internal equipment flashovers, blown fuses, and the violent rupture of the capacitor cans themselves. Properly evaluating and mitigating these transients during the design phase is the only way to prevent these cascading failures and ensure the long-term reliability of the substation.

III. TECHNICAL CLASSIFICATION OF CAPACITOR BANK SWITCHING

To properly evaluate whether a switching device can withstand the transient duties of energization, it is first necessary to classify the type of switching event occurring at the substation. Industry standards broadly divide these events into two categories: single bank switching and back-to-back switching.

A. Single (Isolated) Capacitor Bank Switching

According to IEEE Std C37.012-2022, single capacitor bank switching is defined as the "switching of a capacitor bank whose inrush current is limited by the inductance of the source, buswork inductance, and its own capacitance". A capacitor bank application is technically considered "single" if the transient inrush current magnitude on energization remains less than 20 times the nominal power-frequency capacitive current of the bank. Because the system's source inductance (Ls) is typically large, it limits the charging current. As a result, the transient inrush current during single bank switching is relatively low in both magnitude and frequency, meaning it rarely poses a threat to the making capability of a properly sized switching device.

B. Back-to-Back Capacitor Bank Switching

Conversely, back-to-back capacitor bank switching occurs when a capacitor bank is energized in close electrical proximity to one or more already-energized capacitor banks. In this scenario, the energized banks act as a localized, low-impedance energy source that rapidly discharges into the uncharged bank. Because the limiting inductance in this local loop (Leq) consists only of the short buswork and connections between the stages, rather than the much larger system source inductance, the resulting inrush current can be extremely high. The standards note that back-to-back inrush currents generally exceed 20 times the nominal steady-state current, and can easily reach tens of kiloamperes at frequencies ranging from 2 kHz to over 15 kHz. This is the condition that most frequently damages switching devices and necessitates mitigation.

C. Calculating Inrush Current (I) and Frequency (f)

To ensure that a switching device is applied safely within its tested capabilities, or to determine if Transient Limiting Inductors (TLIs) are required, engineers must precisely calculate the expected peak inrush current (Ipeak) and the natural inrush frequency (fi) of the circuit.

The governing analytical formulas for these calculations are established in IEEE Std C37.012-2022, Table 1 (Inrush current and frequency for switching capacitor banks). These equations provide the mathematical framework for evaluating both single-bank and complex multi-stage back-to-back configurations. The VarStec Capacitor Bank Peak Inrush Analysis Tool utilizes these exact standardized equations, incorporating the necessary multipliers for system overvoltage and maximum positive capacitance tolerance, to automatically calculate the transient duty and verify it against the selected switching device's specific technology and classification limits.

IV. DEVICE TECHNOLOGIES, CLASSIFICATIONS, AND EVALUATION CRITERIA

Calculating the peak inrush current (I) and natural frequency (f) of a switching event is the first half of the engineering challenge. The second, and often more complicated half is properly evaluating those calculated stresses against the limits of the chosen switching device. The evaluation criteria vary drastically depending on the specific standard governing the device, its interruption technology (vacuum, SF6, or oil), and its specific capacitive switching classification.

Understanding the nuance between these different equipment types highlights the complexity of modern substation design and demonstrates why a dedicated analysis tool is essential.

A. Capacitor Switches (Vacuum and SF6)

Dedicated capacitor switches are governed by IEEE Std C37.66-2021 and are specifically designed for the routine switching of capacitive loads. For these devices, the primary evaluation compares the calculated peak inrush current (inclusive of overvoltage and capacitance tolerances) against the device's Rated Transient Peak Inrush Current. Because modern vacuum and SF6 interrupters are not sensitive to the hydraulic shock waves that plague older technologies, IEEE C37.66 explicitly states that there is no upper limit to the natural inrush frequency, provided the peak current magnitude remains within the rated limit.

B. Circuit Breakers: Restrike Classifications (C0, C1, C2)

When circuit breakers are used for capacitor switching, they are governed by IEEE Std C37.04-2018 and IEEE Std C37.012-2022. A critical first step in evaluating a circuit breaker is determining its restrike probability class:

Class C0 (General Purpose): These breakers have an unspecified probability of restrike. Under modern standards, Class C0 devices are not permitted for back-to-back capacitor switching applications due to the high risk of restrikes and resultant overvoltages.

Class C1 (Definite Purpose): These breakers have a low probability of restrike and are generally acceptable for infrequent switching duties according to the standards. VarStec, however, recommends C2 rated breakers for all multi-stage capacitor banks.

Class C2 (Definite Purpose): These breakers have a very low probability of restrike and are explicitly recommended for substation capacitor banks that undergo routine switching.

C. Modern Circuit Breakers (Vacuum and SF6)

For modern Class C1 and C2 circuit breakers, the continuous current rating must first be verified. The continuous current of the breaker must be at least 1.35 times the nominal bank current for grounded wye banks, or 1.25 times for ungrounded banks, to account for system overvoltage, capacitance tolerance, and harmonic currents.

For the transient check, the calculated peak inrush current is compared against the breaker's Rated Back-to-Back Capacitor Bank Transient Peak Inrush Making Current (Ibb). Regarding frequency, IEEE C37.012-2022 permits the natural inrush frequency to exceed the tested frequency as long as the calculated current-frequency product (I x f) does not exceed four times the rated tested product.

D. Legacy Circuit Breakers (Oil)

Although modern substations utilize vacuum and SF6 technologies, engineers frequently encounter legacy bulk oil or minimum oil circuit breakers when substations are being partially upgraded. Oil interrupters are highly sensitive to the high di/dt of transient inrush and outrush currents, which can create violent hydraulic shock waves capable of shattering the interrupter nozzles. Consequently, oil circuit breakers are subjected to strict, highly restrictive limits based on historical criteria. For example, legacy Class C0 oil breakers are limited to peak inrush currents of 1.41 x Isc or 50 kA (whichever is less), and the product of the peak current and frequency (I x f) is strictly limited to 20,000 kA·Hz.

E. The VarStec Tool Advantage

Navigating this web of variables, determining whether to apply the multiplier for a modern vacuum breaker, enforcing a strict 20,000 kA·Hz limit for an older oil breaker, verifying the 1.35x continuous current safety factor, or simply knowing that a Class C0 breaker is invalid for back-to-back switching, is incredibly tedious and error-prone when done manually.

The VarStec Capacitor Bank Peak Inrush Analysis Tool eliminates this complexity. By simply selecting the device technology (Switch or Breaker, Vacuum/SF6 or Oil) and its classification (C0, C1, or C2), the tool automatically applies the correct physics-based rules and standard-specific limits. It provides an immediate, defensible Pass/Fail analysis with a user-defined engineering margin, ensuring the substation design is fully compliant with the latest IEEE guidance while eliminating unnecessary guesswork.

V. MITIGATION STRATEGIES FOR EXCESSIVE TRANSIENT DUTIES

When the calculated peak inrush current or the current-frequency product (Ixf) exceeds the specific nameplate ratings of the selected switching device, the equipment is at risk of sustaining severe contact damage. In these cases, the design engineer has two primary options: either add series inductance to the circuit to reduce the transient energy, or switch to a more advanced, suitable switching technology equipped with built-in transient mitigation or higher ratings.

A. Adding Inductance (Transient Limiting Inductors)

The most common and cost-effective method for controlling back-to-back inrush currents is installing fixed series inductors, known as Transient Limiting Inductors (TLIs) or inrush reactors. By increasing the total loop inductance between the energized and unenergized stages, both the peak current magnitude and the transient frequency are directly reduced to safe levels. For practical application, typically 40 μH to 80 μH of total loop inductance is more than sufficient to protect the switching device at the 15 kV level. At the 34.5 kV level, typical required values range from 80 μH to 160 μH.

B. Point-on-Wave (POW) / Zero Voltage Switching

If the installation of standard TLIs is not desired, advanced switching technologies can be utilized. Independent pole circuit breakers using point-on-wave (POW) or zero-voltage closing controls, such as the ABB VD4-CS™ vacuum circuit breaker, achieve transient-free switching (in both opening and closing operations) by timing the contact closure of each phase to exactly match the system voltage zero. Applying a device with this advanced synchronous control removes the requirement for a transient inrush reactor entirely. An additional, highly valuable benefit of POW switching over a straight TLI application is that the system voltage transient upon energization is also effectively eliminated, improving overall power quality on the network.

C. Pre-Insertion Resistors

Another advanced switching option involves pre-insertion resistors. Devices such as the Southern States CapSwitcher™ utilize a specialized mechanism that temporarily places a resistor in series with the circuit just milliseconds before the main contacts close. This pre-inserted resistance heavily damps the circuit, limiting both the transient inrush current flowing through the device and the voltage transient seen by the broader electrical system. Similar to POW technology, devices utilizing pre-insertion resistors do not require the addition of external transient inrush reactors.

D. Harmonic Filter Banks

It is important to note that when designing harmonic filter banks, dedicated transient inrush reactors (TLIs) are fundamentally unnecessary. The main tuning inductor (whether an iron-core or large air-core reactor) used to form the harmonic filter is many times larger than a traditional inrush reactor. When evaluated in the VarStec Capacitor Bank Peak Inrush Analysis Tool, inputting this massive tuning reactor value significantly increases the total loop inductance (Ltotal). This drastically reduces both the calculated Peak Inrush Current (Ipeak) and the natural inrush frequency (f), ensuring the transient making duty easily meets the "PASS" criteria for the switching device limits.

Based on the field experience of VarStec Engineers, the tuning reactor provides such significant series impedance that transient voltages associated with energization (closing) are almost non-existent. They are reduced to a barely perceptible level on an oscillogram and pose no concern to the switching device or the power quality of the electrical grid during closing.

Standard capacitor banks, despite their fundamental benefits, inherently create a concern for harmonic amplification and resonance. While applying a standard switching device with transient limiting inductors (TLIs) is generally the least expensive design, this setup only mitigates inrush current and does not resolve system voltage transients. To eliminate transient voltages, engineers often look to Point-on-Wave (POW) switching. While POW technology removes the requirement for TLIs (offering some equipment cost reduction), the advanced switching device itself adds significant expense, making the overall capacitor bank more costly.

As a highly effective alternative, incorporating a tuning reactor to form a harmonic filter inherently removes both the transient voltage concern and the transient inrush current concern, while simultaneously eliminating the risk of harmonic resonance. Because the cost of adding a tuning reactor can be comparable to the cost premium of upgrading to a POW switching device, it helps economically justify a vastly better technical solution. VarStec closely evaluates all of these alternatives, balancing transient mitigation, resonance avoidance, and equipment costs, as part of our comprehensive "system fit solution" for our clients.

VI. CONCLUSIONS

Capacitor bank switching is a highly complex transient event that places immense electrical and mechanical stress on switching devices. Proper evaluation of high-frequency inrush and outrush (the subject of another VarStec Engineering Brief) currents is not just a compliance exercise, it is fundamental to preventing unseen contact damage, subsequent restrikes, and catastrophic equipment failures.

Mitigating these risks requires a "system fit" solution. It is not enough to simply pick a switching device off a shelf; the entire installation must be holistically coordinated. The sizing of transient limiting inductors (TLIs), the specific switching technology (vacuum or SF6), the device's restrike classification (C1 or C2), and the system's exact fault characteristics must all be engineered together to seamlessly fit the specific demands of your power system.

The VarStec Capacitor Bank Peak Inrush Analysis Tool (available at VarStec.com) was specifically developed to simplify this process. By automating the rigorous, physics-based calculations and the device-specific pass/fail criteria mandated by the latest IEEE standards, the tool removes the guesswork from equipment evaluation and ensures your substation designs are safe, defensible, and fully compliant.

Beyond providing analytical tools, VarStec Power Solutions is available to partner with you directly. Our team offers comprehensive engineering support to help you evaluate these complex switching transients and design the optimal mitigation strategy. Furthermore, VarStec specializes in the design and supply of completely integrated, standards-compliant metal-enclosed capacitor banks and harmonic filter banks, ensuring that your "system fit" solution is reliable from the design phase all the way through to deployment.

VII. REFERENCES

[1] IEEE Std C37.012-2022: IEEE Guide for the Application of Capacitive Current Switching for AC High-Voltage Circuit Breakers Above 1000 V This guide provides the foundational mathematical formulas for calculating peak inrush current and natural frequency during single and back-to-back capacitor bank switching.

[2] IEEE Std C37.04-2018: IEEE Standard for Ratings and Requirements for AC High-Voltage Circuit Breakers with Rated Maximum Voltage Above 1000 V This standard establishes the mandatory rating structure for circuit breakers, defining capabilities such as continuous current limits, close and latch ratings, and the specific restrike performance classifications (C0, C1, C2) used for pass/fail evaluations.

[3] IEEE Std C37.66-2021: IEEE Standard Requirements for Capacitor Switches for AC Systems (1 kV to 38 kV) This standard defines the specific ratings and testing requirements for dedicated capacitor switches, notably establishing that devices like vacuum switches have no upper inrush frequency limit provided the peak inrush current remains within the tested rating.

[4] IEEE PES-TR16: Transient Limiting Inductor Applications in Shunt Capacitor Banks This technical report details the application and sizing of transient limiting inductors (TLIs) used to mitigate excessive inrush and outrush currents, and also provides historical frequency product limits for legacy oil circuit breakers.

[5] IEEE Std 1036-2020: IEEE Guide for the Application of Shunt Power Capacitors This guide covers the general application of shunt power capacitors and defines the required safety multipliers to account for system overvoltage and maximum positive capacitor tolerance when calculating transient duties.

[6] IEEE Std C37.09-2018: IEEE Standard Test Procedures for AC High-Voltage Circuit Breakers with Rated Maximum Voltage Above 1000 V This document specifies the comprehensive laboratory testing procedures used to physically verify the assigned continuous, short-circuit, and transient recovery voltage ratings of high-voltage circuit breakers.

[7] IEEE Std C37.100.2-2018: IEEE Standard for Common Requirements for Testing of AC Capacitive Current Switching Devices over 1000 V This standard outlines the specific common testing requirements tailored for demonstrating the capacitive current switching abilities and restrike probabilities of switching devices

VIII. VITAE

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