POINT-ON-WAVE VS. PRE-INSERTION RESISTOR TECHNIQUES IN CAPACITOR BANK SWITCHING

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Abstract - The aim of the present work is to compare two different switching techniques for capacitor bank energization and de-energization. Nowadays capacitor banks are used more and more to ensure reactive power compensation and voltage regulation. It is required to change reactive power based on system needs, which means for individual capacitors to be switched in or out many times on daily basis. Energizing capacitor banks can result in harmful overvoltage and overcurrent transients, especially if switched by traditional circuit breakers. Some mitigation means like pre-insertion resistors, inrush limiting reactors, and synchronous switching can mitigate the transients but not all of them are able to fulfill their duty in the same manner. Synchronous switching and pre-insertion resistor provide added advantages in reducing both current and voltage transients, but even among them, there are differences in their performance.

Index Terms — Switching transients, mitigation, energization, de-energization, Back-to-back switching, shunt capacitors, power system studies, capacitive currents, point of wave switching, pre-insertion resistor.

I. INTRODUCTION

Capacitor banks play a crucial role in power systems and industrial applications. They are used more and more in a wide variety of applications providing several advantages like improving power factor, ensuring voltage regulation and maintaining grid stability.

Capacitor banks are particularly used in industrial applications especially for power factor correction of loads, ensuring reduced system losses and an efficient energy management.

In transmission and distribution area, reactive power compensation ensures a better performance reducing energy losses along lines, increasing the system capacity and improving voltage regulation.

In modern renewable energy plants, especially solar and wind, capacitor banks are widely adopted to improve power quality and grid stability. The randomness of the output power due to moving clouds and wind fluctuations can cause rapid changes at the point of common coupling of the renewable plant and the distribution system, especially in weak systems.

In order to ensure a large-scale renewables in medium voltage distribution systems without limiting power capacity, capacitor banks are connected in parallel to generation, to compensate the reactive power and ensure grid stability.

In most of the applications mentioned above, reactive power must be adjusted according to system requirements, which involves switching individual capacitors in and out multiple times each day. This frequent operation, however, introduces challenges: energizing capacitor banks can produce harmful overvoltage and transient overcurrent, particularly when traditional circuit breakers are used. Likewise, de-energizing can cause restrikes, posing a risk of damage to the capacitor bank, the switching device, and other connected components. This is why transient processes of capacitors switching should be smoothed as much as possible.

It is well established that mitigation techniques such as pre-insertion resistors, inrush limiting reactors, and synchronous switching can significantly reduce switching transients. However, their performance varies, and not all methods provide the same level of reliability in mitigating these phenomena. Some techniques are effective only against specific types of transients, while others fail to address different conditions. Among the available solutions, synchronous switching and pre-insertion resistors offer additional advantages by reducing both current and voltage transients, although even between these two approaches, notable differences in performance remain.

The pre-insertion resistor (PIR) technique is a traditional approach for reducing transients by momentarily inserting resistor into the capacitor switching circuit. Typically, this resistor is introduced through an auxiliary set of contacts (Fig. 1) approximately 10 to 15 milliseconds before the main contacts close.

The synchronous switching technique, also referred to as point-on-wave (POW) switching, enables the controlled opening and closing of individual circuit breaker poles while minimizing stress on the equipment (Fig. 2). By eliminating the inherent randomness of mechanical switching, this method uses precise timing algorithms, supported by voltage sensors and servomotor-based actuators, to determine the optimal instant for contact closure or separation.

The aim of the present work is to compare synchronous switching and pre-insertion resistor technique for capacitor bank energization, based on electromagnetic transient simulations on a real case study. Both the currents and overvoltages transients are evaluated to identify the best solution to mitigate the phenomena. An additional comparison on the de-energization process is carried out.

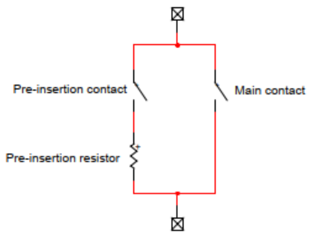

Fig. 1. Pre-insertion resistor (PIR) schematic, single phase.

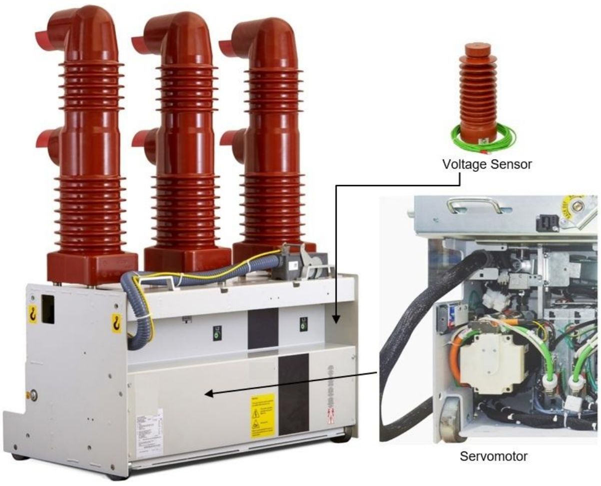

Fig. 2. Point-on-wave circuit breaker.

II. CAPACITIVE SWITCHING BACKGROUND

Capacitive switching duties involve both the energization and de-energization of capacitor banks. Capacitor bank energization produces high inrush currents across the breaker contacts, especially when load voltage and source voltage are not well synchronized. During a making operation, when the dielectric withstand of the interrupter drops below the source voltage, a breakdown may occur before the contacts fully close. As a consequence, a pre-arcing high inrush current starts to flow until the contacts touch, causing melting and protrusions on the contact surfaces. These protrusions can affect the breaker's capability to withstand the recovery voltage during subsequent capacitor bank de-energization, potentially leading to restrikes. This also increases contact wear.

Capacitor bank de-energization stresses the breaker due to a high recovery voltage that can reach up to 2 p.u. after a single-phase current interruption. The value of 2 p.u. is reached in the worst-case scenario when the interruption occurs at the peak of the phase voltage. When the breaker opens, the load-side capacitor remains charged and discharges only through its internal resistance; therefore, the voltage remains on the capacitor for several seconds or even minutes. In a three-phase system, the transient recovery voltage peak can reach up to 2.5 p.u. [1].

High peaks of transient recovery voltage may cause a dielectric breakdown in the gap between the breaker contacts, results in the resumption of current through the breaker contacts causing a restrike. If a restrike occurs the capacitor will be either discharged until the high frequency current is interrupted again. If further restrikes happen, recovery voltage could escalate more and more. Based on that it becomes clear why multiple restrikes should be avoided as much as possible.

Based on the above, capacitive switching is a demanding duty for a breaker and the associated transients can be harmful for power systems and their components. International standards like IEC 62271-100 [2] for high voltage alternating current circuit breakers, require stringent tests to classify the devices based on their probability to experience restrikes during capacitive switching.

Capacitive switching test duties are not a mandatory requirement for circuit breakers. In case breakers are employed to manage charging current of an unloaded transmission line or cable or the load current of a shunt capacitor bank, then the test is required to prove the restrikes performance of the breaker.

The following two classes are specified with respect to capacitive load switching:

- Class C1: circuit-breaker with low probability of restrike during capacitive current breaking.
- Class C2: circuit-breaker with very low probability of restrike during capacitive current breaking.

III. CASE STUDY

The aim of the present work is to compare the POW and PIR techniques for capacitor bank energization, based on electromagnetic transient simulations on a real case study. The comparison between the two transient mitigation solutions is carried out on a typical 33kV medium-voltage system fed by a 90MVA 118/33 kV transformer. Connected to the 33kV busbar is the equivalent load (28.3MVA, power factor 0.85) for which power factor correction is required.

At the same busbar the power factor correction capacitor banks are also installed. Reactive power of capacitors is 7Mvar, which is sufficient to increase the equivalent system power factor to 0.95. Fig. 3 shows the single line diagram of the case study.

The comparison is carried out in three different scenarios:

- Single bank energization in presence of fully discharged isolated capacitor bank
- Single bank energization in presence of fully charged isolated capacitor bank
- Back-to-back energization in presence of fully discharged isolated capacitor bank.

For the back-to-back energization case scenario, an additional capacitor bank of 7MVAr is installed at the same busbar to reach a total reactive compensation power of 14MVAr. In this case the equivalent load power is 56.6MVA with a 0.85 power factor.

All the three scenarios are evaluated in terms of energization considering both the pre-insertion resistor (PIR) and the point-on-wave (POW) techniques.

Finally, an additional case scenario is evaluated to compare capacitor bank de-energization with PIR and POW.

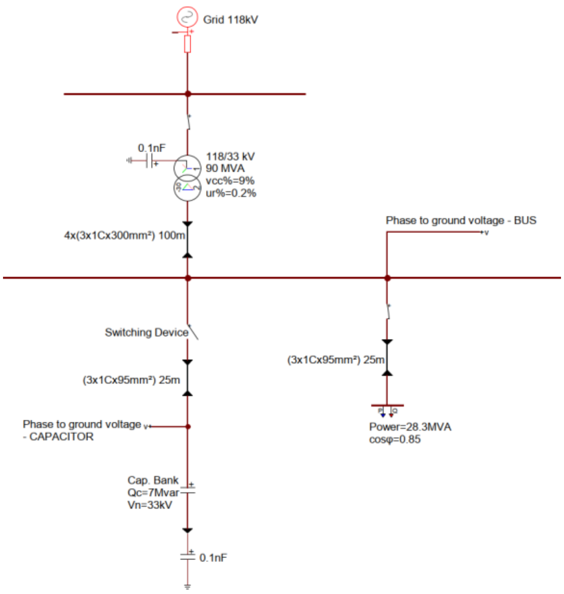

Fig. 3. Case study single line diagram (SLD).

IV. SINGLE BANK ENERGIZATION

Single-bank energization refers to the closing operation of a capacitor bank that generates current and voltage transients when no other capacitor bank is energized on the same busbar.

The amplitude and frequency of the inrush current depend primarily on the short-circuit level at the point of common coupling (PCC). The closing instant relative to the system voltage waveform is also critical, as it directly affects the inrush magnitude. Assuming no residual charge, and considering that capacitor voltage cannot change instantaneously, the closing operation forces the terminal voltage to collapse to zero, producing a severe transient. In a single-phase ideal system, the worst inrush occurs when energization takes place at the voltage peak; the same phenomenon appears in three-phase systems, although with greater complexity.

As previously discussed, Point-on-Wave (POW) switching and Pre-Insertion Resistor (PIR) techniques can mitigate these transients. Their performance is evaluated through electromagnetic transient simulations based on the single-line diagram in Fig. 3, energizing an isolated capacitor bank with no residual charge.

In the baseline scenario, where no mitigation technique is applied, the energization produces an inrush current peak of 16 p.u. (Fig. 4). Under these conditions, the current exhibits a superimposed high-frequency component associated with the L-C resonant frequency of the source and capacitor bank.

For PIR-based energization, typical resistor value between 10 and 90Ω is considered (TABLE I), and the main contacts bypass resistors after an average time of 10ms.

The transient-mitigation effectiveness of POW and PIR is evaluated through the following metrics:

- Peak of inrush current, p.u. (referred to peak current)
- Maximum voltage dip, p.u. (referred to system peak voltage)
- Overvoltage Peak, p.u.

As far as PIR is concerned, two subsequent transients should be taken into account. The first transient is associated with the closing of the pre-insertion contact, which inserts the resistor into the circuit. The second transient occurs when the main contacts close and bypass the resistor (see Fig. 5).

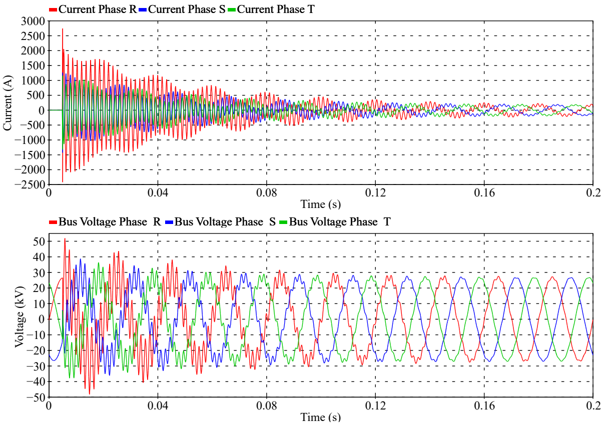

Fig. 4. Energization without mitigation means.

TABLE I
SINGLE BANK ENERGIZATION WITH PIR

Pre-insertion resistor					
	1st transient			2nd transient	
PIR [Ω]	Inrush current [p.u.]	voltage dip [p.u.]	voltage peak [p.u.]	inrush [p.u.]	voltage peak [p.u.]
10	8.61	1.04	1.34	1.85	1.03
40	3.35	0.82	1.06	4.84	1.20
90	1.71	0.62	1.04	8.94	1.43

TABLE II
SINGLE BANK ENERGIZATION WITH POW SWITCHING

POW switching		
Inrush current [p.u.]	voltage dip [p.u.]	voltage peak [p.u.]
1.95	negligible	1.07

The results in Tables I and II indicate that both techniques significantly reduce the transient phenomena associated with capacitor energization. However, notable differences exist between the two approaches.

PIR reduces transients, but its performance strongly depends on the resistor value. Additionally, the presence of two sequential transients complicates system behavior: depending on the chosen resistance, the second transient may be more severe than the first. Moreover, the pre-insertion resistor does not fully eliminate the voltage dip at the PCC, which may affect sensitive equipment.

In detail:

- higher resistance values are more effective in limiting the first transient, reducing inrush current and minimizing voltage dip when energizing unloaded banks. On the downside, a higher resistance increases the current during the second transient and causes greater voltage fluctuations in the system.
- lower resistance values help reduce the impact of the second transient, resulting in lower inrush currents and less stress from transient overvoltages on the system. However, a lower resistance offers limited mitigation during the first insertion transient, leading to higher inrush currents and a more pronounced voltage dip on the system.

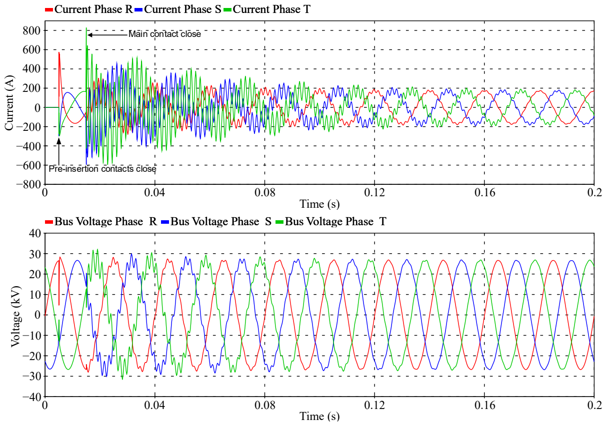

Fig. 5. Single-bank energization with PIR (40Ω).

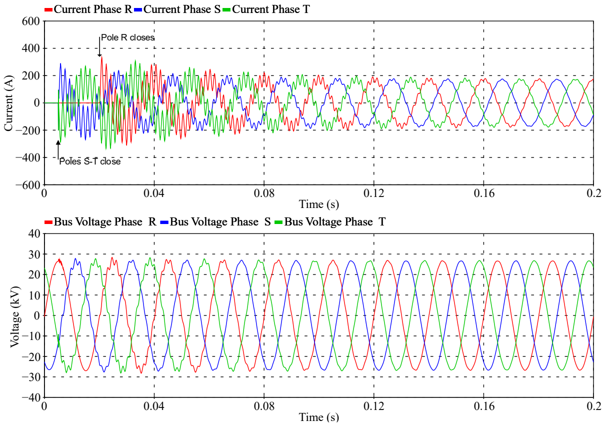

Fig. 6. Single-bank energization with POW switching.

Although resistor values typically range between 10 and 90 Ω, selecting an optimal value requires system-specific tuning, which reduces interchangeability between plants.

Based on results in TABLE I, the optimal resistance value is 40Ω for the evaluated scenario. Overall, the use of PIR limits only some transient phenomena with limited effectiveness in reducing the voltage dip.

In addition, since the resistor value must be optimized based on system configuration, the interchangeability of the solution between different plants becomes difficult.

POW switching, by contrast, consistently minimizes both inrush current and transient overvoltages, while completely avoiding voltage dips during energization (see Fig. 6).

Thanks to this superior performance, breakers controlled with POW technique ensure reduced contact wear and consequently can reach a higher number of operations before maintenance.

At the same time the interchangeability between different plants is easier compared to PIR.

Nowadays, technical solutions are available on the market that embed POW for both energization and de-energization, while also providing short-circuit protection duty. All these features can be obtained by installing a single device.

The data presented in Table II clearly demonstrates the superior performance of Point-on-Wave (POW) switching compared to Pre-Insertion Resistor (PIR) techniques. While PIR can reduce the initial transient, its effectiveness is strongly dependent on the resistor value, which introduces design complexity and limits interchangeability across different installations. POW, on the other hand, provides consistent results regardless of the system impedance or capacitor characteristics, making it a more universal solution.

From a practical perspective, the absence of voltage dips when using POW is a critical advantage for sensitive industrial processes. Voltage dips, even of short duration, can lead to malfunctions in automation systems, variable speed drives, and other electronic equipment. By eliminating this issue, POW ensures higher process reliability and reduces the risk of costly downtime.

Maintenance considerations further differentiate the two technologies: PIR-based systems require periodic inspection of resistors and auxiliary contacts to prevent degradation, whereas POW-controlled breakers, equipped with servo-motor technology, experience reduced contact wear and longer maintenance intervals. This translates into lower lifecycle costs and improved operational efficiency.

In summary, POW better aligns with modern grid requirements for flexibility, reliability, and integration of renewable energy sources, where power quality and operational continuity are paramount.

In case a single bank must be de-energized and re-energized within a short period of time, a residual charge trapped in the capacitor can affect the subsequent reclosing operation. This can lead to extremely high transients during the re-energization of the capacitor. Even in this scenario, the adoption of POW and PIR solutions can mitigate transient phenomena. To compare the performance of POW and PIR, transient simulations are carried out in a worst-case scenario, considering the capacitor bank fully charged before energization (TABLE III and IV).

TABLE III
SINGLE BANK RE-ENERGIZATION WITH PIR, FULLY CHARGED BANK

Pre-insertion resistor					
	1st transient			2nd transient	
PIR [Ω]	Inrush current [p.u.]	voltage dip [p.u.]	voltage peak [p.u.]	inrush [p.u.]	voltage peak [p.u.]
40	8.14	1.93	1.16	4.86	1.20

TABLE IV
SINGLE BANK RE-ENERGIZATION WITH POW, FULLY CHARGED BANK

POW switching		
Inrush current [p.u.]	voltage dip [p.u.]	voltage peak [p.u.]
1.10	negligible	1.03

Simulations show that PIR solution limits the inrush current to 8.14 p.u. compared to POW, which is capable of reducing the inrush to 1.10 p.u.

In this scenario as well, the voltage dip associated with PIR energization can reach levels that may affect sensitive equipment.

POW manages the reclosing operation by continuously monitoring the residual charge on the capacitor and selecting the optimal closing instant to minimize transients.

Once again, POW does not introduce any voltage dip on the system and significantly reduces contact wear, increasing equipment lifetime.

V. BACK-TO-BACK ENERGIZATION

Back-to-back energization is the closing operation of a capacitor bank when other banks connected to the same busbar are already energized. In this condition, the resulting transient is mainly due to current exchange between the banks. This current can reach extremely high amplitudes and frequencies, potentially exceeding the capability of the switching device. Without any mitigation technique, back-to-back energization results in an extremely severe transient, with the inrush current reaching a peak value of 116 p.u. (Fig. 7). Such a magnitude highlights the criticality of the phenomenon and confirms the need for dedicated switching strategies to ensure equipment protection and operating reliability.

As shown in TABLE VI, the adoption of POW significantly mitigates these transient phenomena, whereas PIR is not able to reduce the inrush peak to comparable levels. A comparison between PIR and POW is reported in TABLE V and TABLE VI.

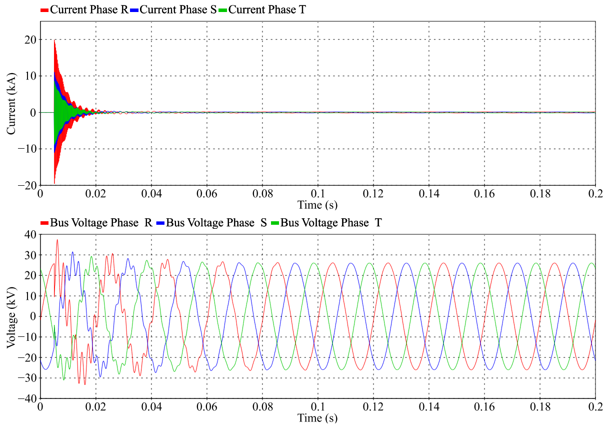

Fig. 7. Energization without mitigation means.

TABLE V
BACK-TO-BACK ENERGIZATION WITH PIR

Pre-insertion resistor					
	1st transient			2nd transient	
PIR [Ω]	Inrush current [p.u.]	voltage dip [p.u.]	voltage peak [p.u.]	inrush [p.u.]	voltage peak [p.u.]
10	15.67	0.27	1.29	8.09	1.03
40	3.92	0.18	1.14	30.26	1.10
90	1.73	0.15	1.06	61.11	1.22

TABLE VI
BACK-TO-BACK ENERGIZATION WITH POW

POW switching		
Inrush current [p.u.]	voltage dip [p.u.]	voltage peak [p.u.]
1.79	negligible	1.07

In back-to-back energization using PIR, the voltage dip is lower than in single-bank energization, as system voltage is sustained by the bank already connected to the same busbar.

On the other hand, POW switching confirms its ability to avoid any voltage dip while providing superior performance in reducing inrush current. This behavior is illustrated in Figs. 8 and 9, which align with results reported in TABLES V and VI.

To better understand these transient behaviors and the differences between PIR and POW, accurate simulation is essential, as electromagnetic transient programs use microsecond-scale time steps to capture the high-frequency oscillations that occur during switching.

From a design perspective, circuit breakers must not only withstand peak inrush currents but also maintain mechanical integrity over thousands of operations. POW-controlled breakers integrate sensors and actuators for precise synchronization with the voltage waveform, reducing stress on contacts and extending service life. This precision is particularly valuable in industrial environments where downtime incurs significant costs.

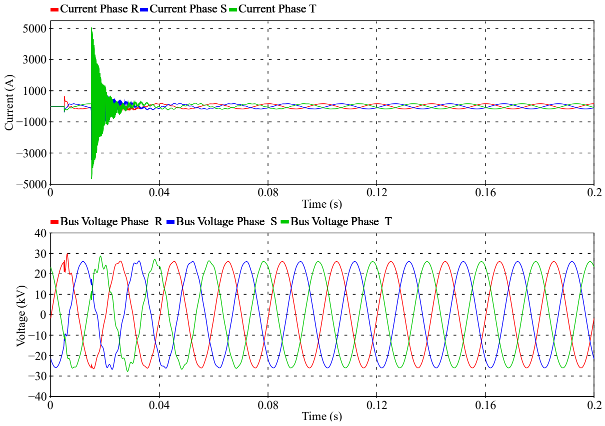

Fig. 8. Back-to-back bank energization with PIR (40Ω).

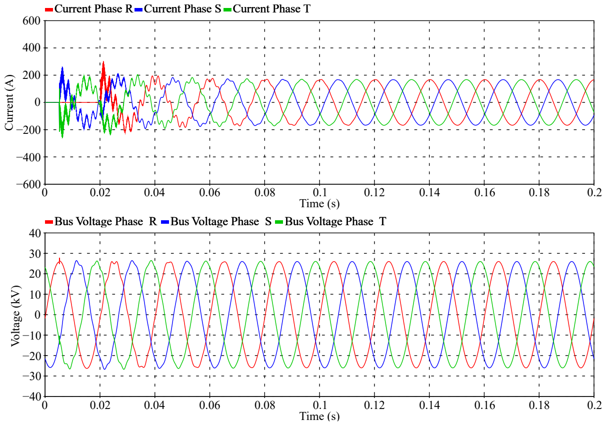

Fig. 9. Back-to-back bank energization with POW.

In applications such as steel mills, oil and gas, chemical plants, and renewable energy facilities, where capacitor banks are switched frequently, the cumulative benefits of POW become evident. By reducing voltage dips and minimizing inrush currents, POW enhances power quality and supports the growing need for resilient and flexible grid operations.

VI. CAPACITOR BANK DE-ENERGIZATION

Another aspect that needs to be considered when comparing POW or PIR devices is the capability to de-energize capacitor banks.

Controlled opening of capacitor banks is a critical aspect for ensuring system reliability and minimizing equipment stress. When contacts separate near the current zero crossing, the dielectric gap may be insufficient to withstand the transient recovery voltage (TRV), leading to restrikes. These restrikes can cause severe damage to breaker contacts and capacitor units, increasing maintenance costs and reducing operational safety.

In conventional and uncontrolled devices (such as PIR), contact separation may occur close to the current zero, so that half a cycle later, the gap between the contacts may still be insufficient to withstand the high transient recovery voltage. In a three-phase system, the transient recovery voltage peak can reach up to 2.5 pu [1].

High peaks of transient recovery voltage may cause a dielectric breakdown in the gap between the breaker contacts, resulting in the resumption of current through the breaker contacts causing a restrike. If a restrike occurs the capacitor will be discharged until the high-frequency current is interrupted again. If further restrikes happen, the recovery voltage may escalate further.

In case circuit breakers are placed to manage charging current of an unloaded transmission line or cable or the load current of a shunt capacitor bank, then a specific test is required to prove the restrikes performance of the breaker. The following two classes are defined with respect to capacitive load switching:

- Class C1: circuit-breaker with low probability of restrike during capacitive current breaking.
- Class C2: circuit-breaker with very low probability of restrike during capacitive current breaking.

Circuit breakers based on POW technology are not only tested to ensure an extremely low probability of restrikes but also address this challenge by synchronizing the opening operation away from the zero-current crossing.

This approach ensures a sufficient contact gap before the TRV peak occurs, significantly reducing risk of restrikes and enhancing breaker longevity.

Moreover, POW devices calculate the optimal opening time, mitigating dielectric stress and extending equipment life, making them particularly suitable for applications requiring frequent switching and high reliability.

VII. CONCLUSIONS

The analysis presented clearly shows that controlled switching solutions, and in particular POW technology, provide superior performance in capacitor bank operations when compared to traditional PIR-based approaches. Both PIR (Pre-Insertion Resistor) and POW (Point-on-Wave) techniques provide effective means to mitigate switching transients; however, the results clearly demonstrate that POW devices deliver superior performance across all critical parameters. While PIR solutions can reduce inrush currents to some extent, their effectiveness is highly dependent on resistor sizing, which introduces design complexity and limits adaptability to different system configurations. In contrast, POW switching offers a modern approach to transient mitigation during both energization and de-energization of capacitor banks. Leveraging servo-motor technology and advanced control algorithms, POW ensures precise timing of contact operations, eliminating voltage dips and significantly reducing inrush currents and transient overvoltages. These benefits translate into improved equipment reliability, extended service life, and reduced maintenance requirements; key factors for industrial environments where operational continuity is critical.

The ability to manage Transient Recovery Voltage (TRV) during de-energization further strengthens POW's position as the preferred solution. By synchronizing opening operations away from zero-current crossings, POW minimizes restrike probability, ensuring safe and efficient breaker performance even under demanding conditions. This controlled approach is particularly valuable in high-voltage applications and installations with frequent switching cycles, such as petrochemical plants, steel mills, and renewable energy facilities.

In industrial environments such as petrochemical plants or renewable energy installations, where operational continuity is paramount, the benefits of controlled opening translate into fewer outages and improved power quality. As electrical networks evolve toward greater complexity, flexibility, and integration of distributed generation, the need for advanced switching technologies becomes paramount. POW aligns perfectly with these requirements, offering a solution that enhances power quality, reduces downtime, and supports the transition to resilient and sustainable grids.

POW for capacitive switching is not just a theoretical concept; it's the state of the art in switching technology. These solutions are already available, and successful installations in real world plants confirm their reliability and superior performance.

Tables VII and VIII illustrate the differences between POW and PIR, providing a clear comparison across all evaluated parameters and operating scenarios. For systems where reliability, efficiency, and operational stability are essential, POW represents the optimal approach for capacitor bank switching.

TABLE VII
EFFECTIVENESS OF PIR AND POW, ENERGIZATION DUTY

		Comparison – Energization		
		inrush reduction	**voltage drop at POC**	**transient overvoltage**
Single bank	**PIR**	good	high voltage drop, resistor dependent	significant, resistor dependent
	POW	superior	no voltage drop	negligible
Back-to-Back	**PIR**	sufficient	significant voltage drop, resistor dependent	significant, resistor dependent
	POW	superior	no voltage drop	negligible

TABLE VIII
EFFECTIVENESS OF PIR AND POW, DE-ENERGIZATION DUTY

	Comparison – De-energization	
	Restrikes probability	**Additional features to avoid restrikes**
PIR	very low probability of restrikes (in case of C2 class device)	not applicable
POW	very low probability of restrikes (in case of C2 class device)	superior performance thanks to controlled switching

VIII. REFERENCES

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[2] IEC 62271-100 High-voltage AC circuit-breakers

IX. VITA

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