Diminution of Transient Disturbances for High Voltage Application Integration

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Abstract. The increasing global energy demand and large-scale renewable energy resources integration have intensified concerns over power system stability, particularly at extra-high voltage (EHV) transmission level. Shunt capacitor banks are widely employed to enhance voltage stability, but their energization often introduces severe transient overvoltage and inrush currents that threaten equipment reliability and grid security. This paper investigates the application of synchronous switching using the Point-on-Wave (PoW) technique as a mitigation strategy for transient disturbances during capacitor bank energization. A two-stage methodology was adopted, combining MATLAB/Simulink-based transient modelling with field implementation at Eskom's 400 kV Delphi Transmission Substation. The simulation results demonstrated that uncontrolled switching produced peak disturbances of 1.04 kA and 479 kV, corresponding to ±480% and 22% transient elevation above nominal levels. By contrast, PoW switching at the zero-crossing reduced peak transients to 539 A and 412 kV, representing reductions of approximately 51% in current and 15% in voltage. Field experiments using a Schneider RPH2 PoW relay integrated with a GE C70 protection relay further validated these results, confirming significant reductions in inrush stress, transient duration, and breaker wear. Beyond technical validation, the study highlights operational benefits including improved equipment lifetime, lower maintenance costs, and enhanced system reliability, critical for renewable-rich and stability-constrained power systems. The findings establish PoW-based switching as a practical and scalable solution for transient mitigation in modern EHV grids.

1 Introduction

Power system stability remains a critical global concern as energy demand rises and renewable energy sources (RES) penetration increases, placing unprecedented stress on existing transmission infrastructure. Voltage stability has emerged as a central challenge for utilities, prompting the widespread use of shunt capacitor banks to support system voltages and improve reactive power margins [1]. While historically applied at distribution or load centres, recent trends have shifted toward integrating shunt capacitor banks at extra-high voltage (EHV) levels as a medium-term solution to manage increased generation injection and delay costly grid reinforcements[2]. However, the energization of capacitor banks at EHV levels introduces severe transient disturbances, including inrush currents and overvoltages, that may compromise equipment integrity [3], initiate unwanted protection operations, and reduce overall system reliability. Maintenance and equipment replacement costs due to equipment performance and failures. Several mitigation techniques have been investigated in the literature, such as pre-insertion resistors, inductor-based switching, and advanced protection coordination [4]. While these approaches offer partial reductions in transient stress, they often involve additional hardware complexity, energy dissipation, or limited adaptability under varying grid conditions. Moreover, much of the prior research has been restricted to simulation-based analyses, with relatively few studies validating controlled switching methods on operational EHV transmission systems

This paper addresses these gaps by investigating the application of synchronous switching using the Point-on-Wave (PoW) technique to reduce transient disturbances during EHV capacitor bank energization [5]. The novelty of this work lies in its two-pronged methodology: (1) a comprehensive simulation study in MATLAB/Simulink to characterize transient behaviour under both uncontrolled and PoW-controlled switching, and (2) experimental validation through field implementation at Eskom's 400 kV Delphi Transmission Substation using industrial-grade relays and testing equipment. This combined approach ensures both theoretical rigour and practical applicability, strengthening the case for large-scale deployment of PoW technology. This paper contributes a comparative analysis of transient reduction under PoW switching, validates the reliability and scalability of PoW-controlled capacitor bank switching in a real EHV environment, and evaluates operational benefits, including improved equipment lifespan, lower maintenance requirements, and enhanced grid availability in renewable-integrated systems. By addressing both the technical and practical dimensions of transient mitigation, this study advances the integration of shunt capacitor banks into modern high-voltage grids and contributes toward improving system reliability under evolving energy landscapes

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2 Literature Review

2.1 Transmission Line Fault Transients

Transient disturbances in the power systems are the variations of current, voltage, and frequency that occur for a short duration [6]. The typical causes for transients are switching operations, fault clearances after short circuit faults, and equipment energization [7]. The equipment energization is related to switching power transformers, capacitor banks, and reactors in the power system.

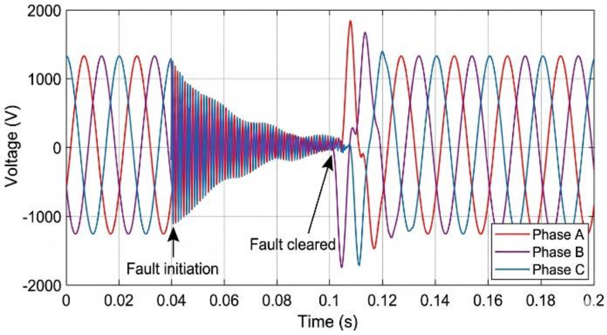

Fig. 1. Three-phase line fault clearance

The illustration in Fig. 1 shows a three-phase fault (LLL) on the transmission line. The protection has operated and initiated a reclosure. The rise in fault current causes a proportional voltage decay to occur until the fault is cleared [8]. The post-fault voltage waveform indicates a voltage transient elevation for a duration of ±10ms. Exposure to frequent reclosures increases the exposure rate to high transient voltage levels, which may exceed the equipment rating and contribute to long-term equipment damage [9].

2.2 Plant Energization Transient Effects

The energization of the power system apparatus results in transient disturbances emerging for a short duration. The result of unsuccessful integration with minimal transient disturbance into the power system is asserted by a protection operation as a result of voltage and current parameters exceeding the protection settings [10]. The adjustment to protection settings decreases sensitively to protect the equipment effectively.

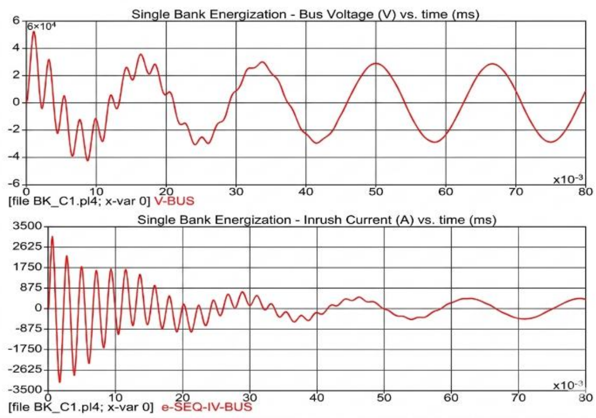

Fig. 2. Capacitor bank energization

Fig. 2 is related to the energization of a shunt capacitor bank. Unsynchronized switching resulted in a transient voltage elevation and duration equating to ±1 pu at ±20 ms. The current elevation and duration equated to ±5 pu at ±3 0ms. The instantaneous voltage and current functions could initiate a trip condition due to the values being exceeded during energization [11]. Therefore, presenting a case of unsuccessful power system integration

2.3 Transient Disturbance Reduction Mechanisms

2.3.1 Pre-Inserting Resistors

The use of pre-insertion resistors (PIR) is a method adopted to reduce inrush current during energization of capacitor banks [12]. Fig. 3 illustrates the basic circuit for the circuit breaker with pre-insertion resistors. During a closing operation of the circuit breaker, the PIR switch and interrupter close synchronously, with the PIR switch being first, and are closed for 8 to 11 ms, followed by the main breaker contacts. This will reduce the momentary inrush current. The short circuit that the main contacts create across the PIR switch forces the current flow through the main contacts. Thereafter, the PIR switch opens after ±8 ms [12].

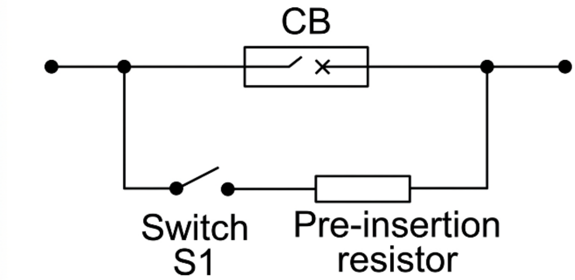

Fig. 3. Preinserting resistor technique

2.3.2 High Inrush Current Generation

Fig. 4 illustrates the busbar and capacitor bank voltages, including the capacitor current, under energization conditions. The transient inrush current is greater than 6 kA at 12 pu, with a duration of ±2 ms, and is a result of the main contact closing position at an instant during a high potential difference between the busbar and capacitor bank voltage. The preinserting resistors are being switched before the main contact, followed by the main contact. However, the main contact will be required to be advanced to a position where zero potential difference exists between the busbar and capacitor bank voltage, which in turn develops minimal inrush current [13].

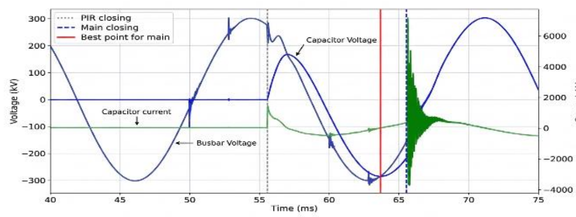

Fig. 4. Switching without pre-insertion resistors

2.3.3 Low Inrush Current Generation

Fig. 5 illustrates the current drawn during a breaker closure at ±56ms. The integration using of preinserting resistors resulted in a current of ±1.5 kA, resulting in a 75% inrush current reduction in comparison to the previous case that produced an excess of 6kA during switching at 66ms. The transient duration for the main contact is now reduced to ±0.5 %.

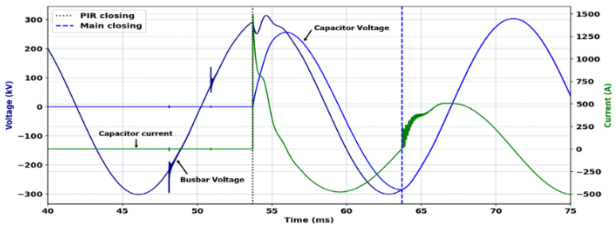

Fig. 5. Switching with pre-insertion resistors

3 POW Switching at Zero Crossing

Fig. 6 represents a basic system of a point-of-wave (POW) switching device used to control the circuit breaker closures. The POW relays are programmed with breaker speed test results. The relay receives an input close command and analyses the zero-crossing point. The relay either advances or delays the breaker close pulse to ensure the main contact of the breaker closes at zero crossing [5]. Table 1 presents the designed simulation parameters.

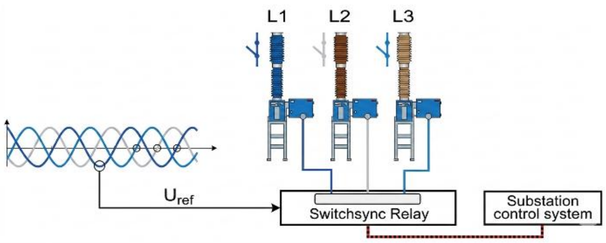

Fig. 6. Point on Wave switching

Table 1. Simulation design parameters.

Model Component	Network Configuration	Design Specifications
Power Source	Interconnected grid	Voltage: 400 kV, 3 Phase Frequency: 50 Hz Grounding: Solidly Earthed
Transmission Line	3 Phase overhead	Voltage: 400 kV, 3 Phase Distance: 80 km
Load	Resistive, Inductive	Voltage: 400 kV, 3 Phase Power: 425 + *j*200 MW
Capacitor Bank	Shunt, Single Star	Voltage:400kV, 3 Phase Power: 100 MVAr
Circuit Breaker	3-phase, Single Pole	Voltage: 400 kV 3-Phase

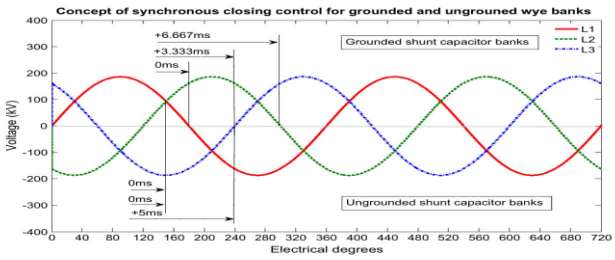

Fig. 7. Point on wave switching sequence

Fig. 7 above depicts the switching sequence for a grounded and ungrounded system at zero crossing. The case study is based on grounded system red phase at 0 ms, followed by the blue phase at 3.3ms, and lastly the white phase pole at 6.667 ms. The closing breaker sequence is RBW.

4 Simulation Modeling and Analysis

4.1 Simulation Modeling

MATLAB Simulink software was used to construct the SCB model and conduct simulation tests. The conditions simulated were synchronized and unsynchronized switching during energization of an SCB.

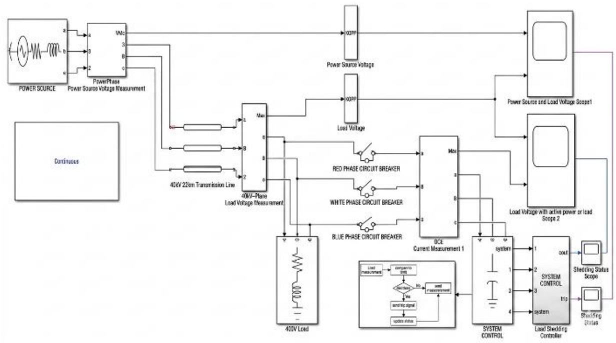

Fig. 8. Power system model for transient analysis

Fig. 8 illustrates the three-phase system breaker closing sequence, RBW, and the times to achieve the zero-crossing switching condition.

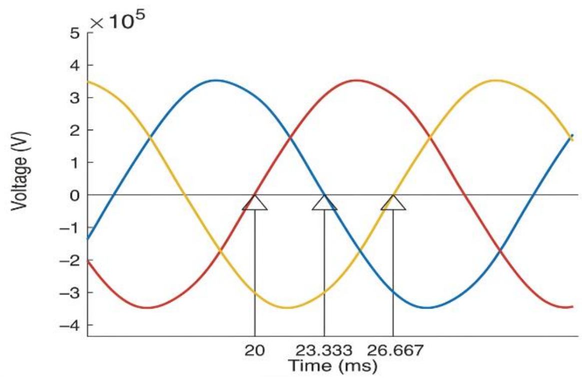

Fig. 9. Simulation at zero crossing

Fig. 9 illustrates the three-phase system breaker closing sequence RBW and the times to achieve the peak switching condition.

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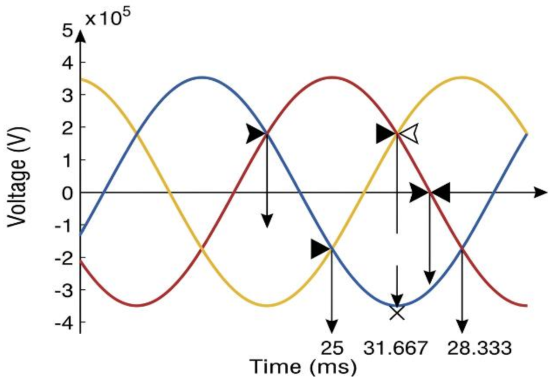

Fig. 10. Simulation at zero crossing

Table 2. Circuit breaker timer settings.

Breaker Phase	*Synchronized Test Close Time(ms)*	*Unsynchronized Test Close Time (ms)*
Red	20	25
White	26.667	31.667
Blue	23.333	28.333

4.2 Simulation Result Analysis

Test results obtained at the zero crossing of the voltage sine wave form of each phase, the sequence of the switching was R, B, W. The switching sequence of the 20.38 ms, 27.14 ms, and 23. 37 ms. The peak currents of the respective phases (R, W, B) obtained were 3.12 pu, 2.86 pu, and 2.56 pu. Minimal deviation from the full load current and transient disturbance was observed, which proves the ideal switching position to which a point on the wave relay should operate.

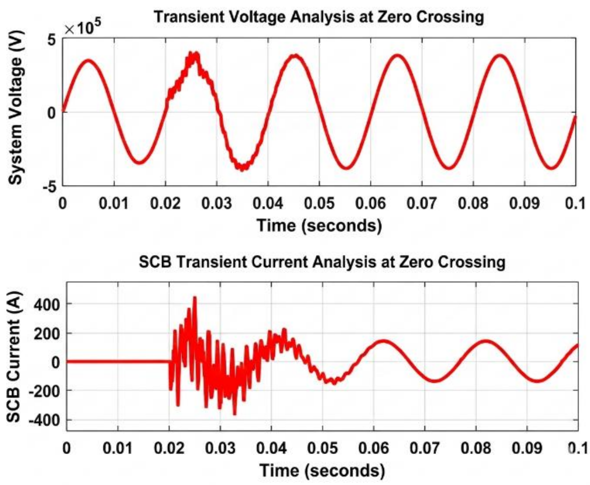

Fig. 11. Simulation at zero crossing red phase

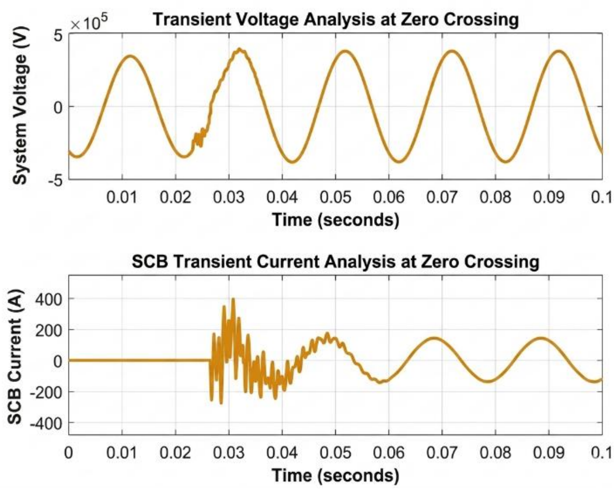

Fig. 12. Simulation at zero crossing white phase

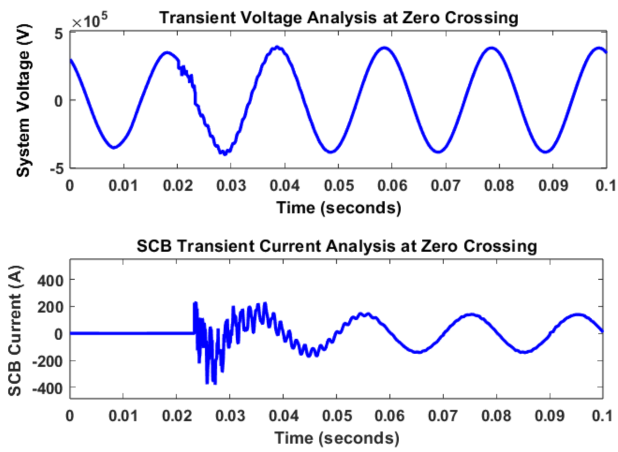

Fig. 13. Simulation at zero crossing blue phase

Table 3. Synchronous switching results.

Phase	Nominal Voltage	Nominal Current	Peak Voltage Measured	Peak Current Measured
Red	400 kV	138.5 A	407.1 kV	433.1 A
White	400 kV	138.5 A	412.4 kV	395.7 A
Blue	400 kV	138.5 A	406.6 kV	354.6 A

Table 4. Unsynchronous switching results.

Phase	Nominal Voltage	Nominal Current	Peak Current Measured
Red	400 kV	138.5 A	980.6 A
White	400 kV	138.5 A	780.2 A
Blue	400 kV	138.5 A	573.3 A

Fig. 14 to Fig. 16 depict the test results obtained at a quarter-cycle angle (π/4) with a 40 ms delay applied to the voltage sine wave. The circuit-breaker switching sequence was R–B–W, with closing times of 25.0 ms, 31.0 ms, and 28.8 ms, respectively. The maximum peak phase currents obtained during energization were 7.10 pu, 5.65 pu, and 4.13 pu, with corresponding transient durations of 37 ms, 32 ms, and 37 ms.

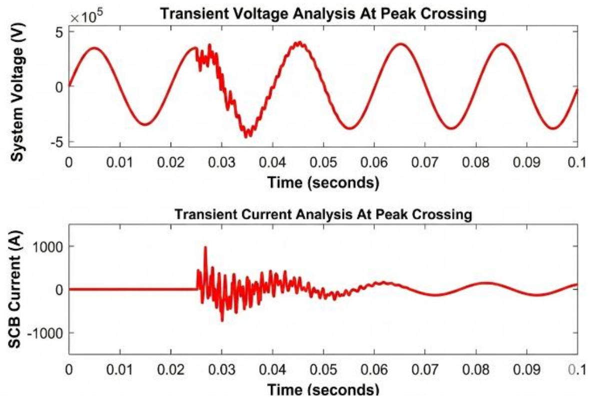

Fig. 14. Simulation at Peak Interception Red Phase

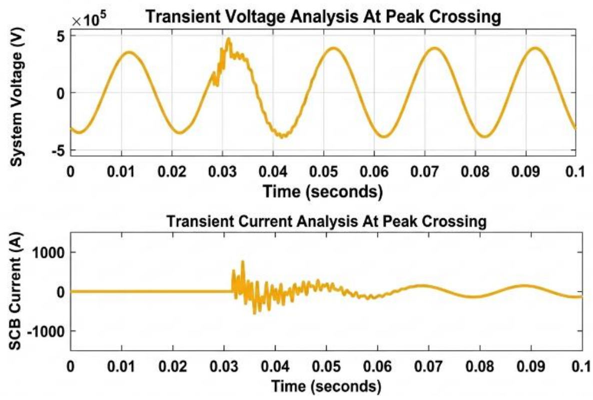

Fig. 15. Simulation at peak interception white phase

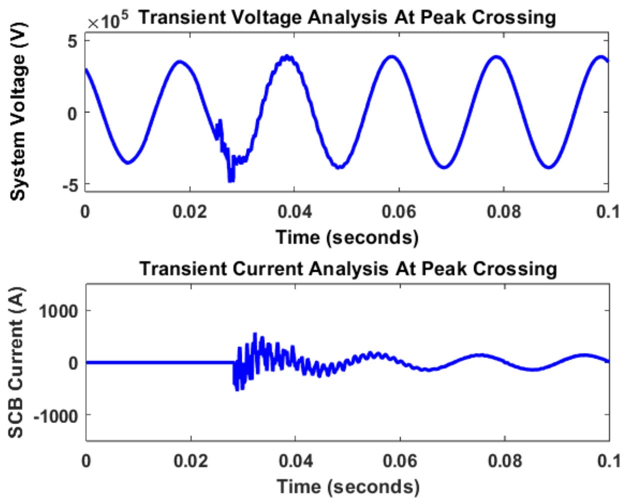

Fig. 16. Simulation at Peak Interception Blue Phase

4.3 Comparative Results Analysis

The comparative results shown in Table 5 proved that by implementing point-on-wave switching, the transient voltage reduction was 13.9% and the inrush current reduction was 51.2%. The reduction of transient voltage from ±20% to ±3.1% was a significant improvement to reduce voltage stress on the plant. There was a significant change in inrush current, which preserves the life span of the circuit breaker and associated equipment.

Table 5. Comparative result analysis.

Parameters	*POW not installed*	*POW installed*
Nominal Voltage	400 kV	400 kV
SCB nominal Current	216.7 A	216.7 A
Peak Voltage	479.3 kV	412.4 kV
Peak current	1.04 kA	539 A
Transient Voltage Duration	±37 ms	±31 ms
Transient Current Duration	39.20 ms	19.53 ms
% Voltage Elevation	± 20%	3.1%
% Current Elevation	± 480%	205%
% Transient voltage reduction against peak	0%	13.9%
% Transient current reduction against peak	0%	51.2%

Case Study

The case study is based on the Delphi 400 kV shunt capacitor bank. The energization was facilitated by the Schneider RPH2 PoW Relay. The case recording represents the field experiment conducted to strengthen the research and demonstrate the contribution to power system sustainability.

Table 6. Delphi SCB design specification

Parameters	Design Rating
MVAr Rating	100 MVA
Nominal Voltage	400 kV
Nominal Current	144.25 A
Bank Configuration	C-Filter
Earthing Method	Single Star Earthed
Fuse Method	Fuseless

Table 6 represents the design parameters for the SCB utilized for the field experiment.

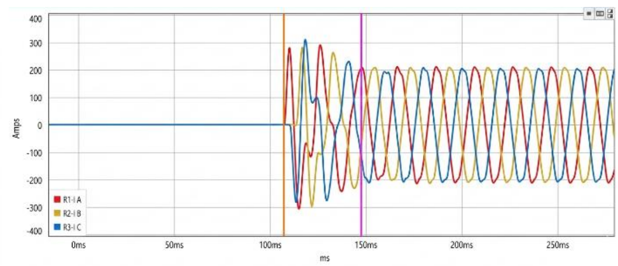

Fig. 17. Inrush current with POW device switching

Fig.17 illustrates the peak current elevation, which showed improvement with the maximum peak current at ±300 A with a transient duration of ±30 ms. The peak current elevation in comparison to the full load current analysed was ±50%.

Table 7. Field vs Simulation Results

Phase	Simulation Nominal current	Simulation Peak Crossing	Field Test Nominal Current	Field Test Zero Crossing
Red	138.5 A	980.6A	144.25 A	283.5 A
White	138.5 A	780.2A	144.25 A	281.2 A
Blue	138.5 A	573.3A	144.25 A	311.2A

The field experiment was conducted using a Point-on-Wave (PoW) switching device to integrate the Extra High

Voltage (EHV) apparatus into the power system under controlled switching conditions. Table 7 presents a comparative analysis between the practical field measurements and the simulation results obtained during the study. In the field test, the PoW switching device was employed to minimize switching transients during energization. The measured maximum inrush current occurred on the blue phase, reaching approximately ±2.0 pu relative to the nominal current of 144.25 A. In contrast, the simulation study was conducted using conventional peak-crossing switching conditions, which produced a significantly higher maximum inrush current of approximately ±7.0 pu against a nominal current of 138.5 A. The comparative analysis, therefore, demonstrates a reduction of approximately ±5.0 pu in inrush current when PoW switching was applied. This substantial reduction confirms the effectiveness of PoW switching in mitigating transient disturbances and improving EHV system stability and operational reliability.

Conclusion

This study has demonstrated that energizing EHV shunt capacitor banks with uncontrolled switching produces substantial transient overvoltages and inrush currents, which can compromise the reliability and longevity of high-voltage infrastructure. Through a combined simulation and field-based approach, the research confirmed that point-on-wave (PoW) synchronous switching provides a robust mitigation mechanism, reducing current transients by up to ±51% and voltage disturbances by ±14%. These reductions not only enhance operational reliability but also significantly alleviate mechanical and dielectric stress on circuit breakers and associated equipment. The field validation at Eskom's 400 kV Delphi Substation demonstrated that the technique is not merely theoretical but a practical approach to reducing transient disturbances.

In addition to its technical merits, PoW switching offers measurable operational and economic advantages, including reduced breaker maintenance, extended equipment service life, and improved grid availability [14]. The approach is also inherently scalable, making it suitable for wider adoption in ultra-high voltage systems and renewable-integrated transmission grids where frequent capacitor bank switching is required. Future work should explore adaptive PoW schemes leveraging machine learning for real-time optimization under variable system conditions, as well as hybrid strategies combining PoW with pre-insertion resistors or controlled inductors for even greater transient suppression [15]. These directions will further strengthen the resilience of evolving power systems facing increasing uncertainty, renewable penetration, and infrastructure stress.

REFERENCES

1. S. Singh, Reactive power management in utility grids with renewable energy, in Renewable Energy Integration in Utility Grids: Elsevier, pp. 115-133, (2025).
2. S. A. Adegoke and Y. Sun, Power system optimization approach to mitigate voltage instability issues: A review, Cogent Engineering, vol. 10, no. 1, pp. --21, (2023).
3. Y. Chen, Y. Liu, J. Fu, W. Liu, W. Kang, and G. Yang, Review of Site Testing Technologies for Converter Transformers, in 2025 IEEE International Conference on Electrical Energy Conversion Systems and Control (IEECSC), IEEE, pp. 923-929, (2025).
4. M. Faiz, The Simulation Analysis of Shunt Reactor Controlled Switching at 500 kV Network, International Journal of Electrical Engineering & Emerging Technology, vol. 5, no. 2, pp. 31-37, (2022).
5. A. Kumar, U. Parikh, and I. Kaur, Application of Point on Wave Switching for Mitigation of Transients During Charging of Power Transformer in Presence of Large Capacitive Component, in International Conference on Emerging Trends and Advances in Electrical Engineering and Renewable Energy, (2020): Singapore, Springer, pp. 189-203.
6. K. P. Nnoli, F. Delić, and S. Kettemann, Transient dynamics and propagation of voltage and frequency fluctuations in transmission grids, IEEE Access, vol. 11, pp. 11307-11328, (2023).
7. A. Aryal, Power System-Fault Clearance with Limited Fault Current, (2024).
8. S. F. Moula and M. T. Ahammed, Analysis of transmission-line faults and auto recloser based protection, in 2021 4th International Conference on Recent Trends in Computer Science and Technology (ICRTCST), (2022). IEEE, pp. 91-95.
9. M. Bindi, M. C. Piccirilli, A. Luchetta, and F. Grasso, A comprehensive review of fault diagnosis and prognosis techniques in high voltage and medium voltage electrical power lines, Energies, vol. 16, no. 21, p. 7317, (2023).
10. N. Mazibuko, K. T. Akindeji, and K. Moloi, A review on the impact of transmission line compensation and RES integration on protection schemes, Energies, vol. 17, no. 14, pp. 123, (2024).
11. A. A. Majeed, A. S. Altaie, M. Abderrahim, and A. Alkhazraji, A review of protection schemes for electrical distribution networks with green distributed generation, Energies, vol. 16, no. 22, pp. 1-27, (2023).
12. L. Chen, X. Chen, Y. Wei, C. Wu, J. Deng, and F. Ma, Study of controlled switching with preinsertion resistor during energization of AC filters, in IET Conference Proceedings CP787, (2021), vol. 2021, no. 15: IET, pp. 1682-1687.

13. F. R. Gadotti, S. H. Cabral, and F. M. Schuartz, Study of deployment of Pre-Insertion resistor to disconnector for mitigating overvoltage on 525 kV current transformers, International Journal of Electrical Power & Energy Systems, vol. 156, pp. 1-19, (2024).
14. N. Zhou, Y. Xu, S. Cho, and C. T. Wee, A systematic review for switchgear asset management in power grids: condition monitoring, health assessment, and maintenance strategy, IEEE Transactions on Power Delivery, vol. 38, no. 5, pp. 3296-3311, (2023).
15. Z. Hao, W. Chen, X. Li, P. Yao, and Y. Wang, Step-Wave AC Collection System: A More Efficient Solution for Wind and Photovoltaic Power Transmission. IEEE Transactions on Industrial Electronics. pp. 1-25, (2025).