Undesired Events of HV Capacitor Banks by Negative Sequence Current Unbalance Protection Under External Faults

Juan F. Piñeros, Divier A. Echeverri, Cristian Arias, Fabian Díaz

Abstract—**Capacitor banks are crucial for providing reactive power support in power systems, including contingency conditions and cascading events. This work presents a comprehensive analysis and proposes a solution for events in 110 kV grids within the Colombia Power System. Specifically, the paper addresses the problem of the undesired tripping of capacitor banks during external faults. These spurious trippings were caused by the operation of the negative sequence unbalance function (ANSI 46) within the capacitor bank protection system, which were implemented considering the guidelines of IEEE C37.99-2012. A detailed simulation study was conducted using EMTP/ATP to analyze the performance of the ANSI 46 function and evaluate its impact on both the equipment and overall power system operation. The simulation results highlighted the need to either verify deeply the understanding of the current IEEE criteria or implement a supervisory function of the ANSI 46 protection to reduce misoperations during external faults. A solution was explored based on the principle of a supervised function to enhance selectivity. EMT simulation tests were carried out to verify the effectiveness of the proposed function, yielding positive results. Finally, several recommendations are provided from the point of view of the power system operator considering the obtained results.**

Keywords—**Capacitor Bank, Negative Sequence Unbalance, Protection Coordination, EMT Protection Simulation.**

I. Introduction

SHUNT CAPACITOR banks (SCB) are a conventional method to support voltage stability in power systems operation globally. SCB are a ubiquitous component of most power systems, deployed across various voltage levels. In high-voltage applications, their primary function is to provide reactive power support, thereby contributing to maintaining voltages within normal operating ranges.

According to The North American Electric Reliability Corporation (NERC) State of Reliability Reports [1], incorrect protection settings remain a leading cause of protection misoperations, as evidenced by power system event statistics. The loss of SCB during external faults in a power system directly impairs voltage stability, and this can increase the magnitude of a blackout if voltage stability is compromised. Furthermore, because a tripped SCB requires a discharge period (usually 10 minutes), before it can be reconnected, the impact on voltage stability can extend over several minutes or even hours.

When faults in transmission lines are cleared with a delay or by backup protection schemes a scenario more prevalent in sub-transmission systems SCB become more susceptible to protection miscoordinations due to undesired premature tripping of some specific protection functions.

This work presents a discussion on the performance of the ANSI 46 unbalance negative sequence current function when applied to high-voltage SCB. The analysis is motivated by instances of undesired tripping observed in the Colombian sub-transmission power system. A further review and discussion, supported by EMT simulations of a real-case scenario, examines the criteria recommended by the IEEE C37.99 guide [2]. Several recommendations and consideration are given regarding the application of the guide's recommendations to increase the security of the operation of SCB.

II. Undesired Events of the ANSI 46 Protection Function in Shunt Capacitor Banks in Colombia

Between 2016 and 2017, four events occurred within the Colombian power system, specifically in the sub-transmission portions of the grid (110 kV and 115 kV), involving unintended disconnection of SCB during external faults due to the activation of the ANSI 46 protection function.

TABLE I
SUMMARY OF FOUR UNCOORDINATED TRIPPINGS OF ANSI 46 SCB PROTECTION FUNCTIONS IN THE COLOMBIAN POWER SYSTEM

No	Capacitor Bank type	Fault type	Faul location	Tripping time SCB, ANSI 46 [s]	Adjacent element tripping time [s]
1	115kV 12.5 Mvar, Y-Y ungrounded	1Ph-g	Adjacent line	0.21	0.433 Zone 2
2	115kV 12.5 Mvar, Y-Y ungrounded	1Ph-g	Adjacent line	0.22	0.427 Zone 2
3	110kV 15 Mvar, Y - grounded	2Ph	medium voltage line	0.25	0.44
4	115kV 15 Mvar, Y-Y ungrounded	1Ph-g	Adjacent line	0.15	0.3 Zone 2

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Table I shows the summary of the events. Two of these events resulted in multiples substations blackouts. These blackouts were triggered by the loss of SCB, which led to reactive power overloads and subsequently increased the number of disconnected substations due to line bay overload openings and considering the behavior of the load with a high motor component.

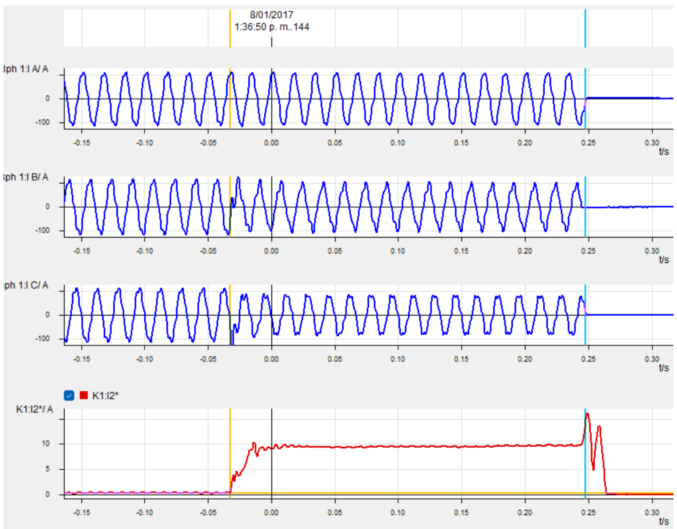

Fig. 1. Capacitor bank 15 Mvar real event undesired trip of ANSI 46 protection function during external fault - phase currents (blue) negative sequence current (red)

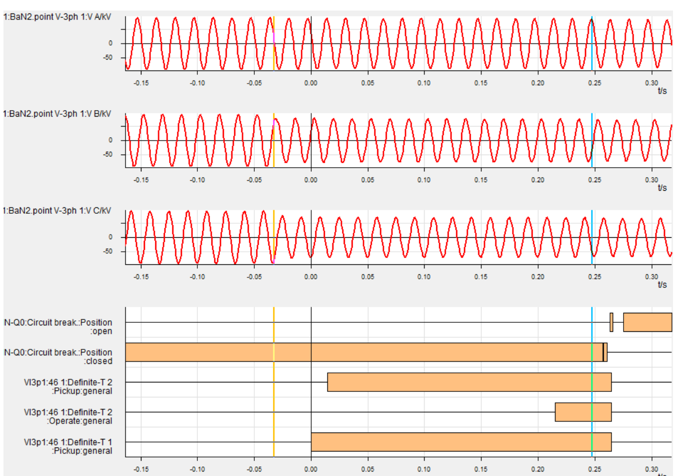

Fig. 2. Capacitor bank 15 Mvar real event undesired trip of ANSI 46 protection function during external fault - phase voltages and digital signals

The SCB involved in these events had ratings from 5 Mvar to 20 Mvar, with tripping times varying between 150 and 450 ms. Fig. 1 and Fig. 2 illustrate, respectively, the current and the voltages waveforms, alongside digital signals, recorded during the event 3 of the Table I involving a 15 Mvar, 110 kV grounded wye capacitor bank.

In general, the events showed that each case involving the SCB topology and adjacent backup protection systems needs to be revisited in order to achieve coordination with the unbalanced SCB protection functions for external faults to the SCB.

The transmission lines associated with these four events lacked pilot protection, relying instead on a primary protection scheme consisting of a single distance relay and an overcurrent relay. For faults occurring near the remote substations where the SCB were located, fault clearing times were contingent upon zone 2 operation, typically ranging from 300 ms to 450 ms, considering detection, tripping and circuit breaker opening times.

Following these events and due to the recurrent trippings, investigations revealed that consulting companies responsible for the protection studies of the affected SCB were using the ANSI 46 protection setting criteria as recommended in the guide IEEE C37.99 [2], without a adequately considering the accompanying considerations.

The guide's criteria for the ANSI 46 protection function, outlined in section 7.1.15, specifies 10% with a delay setting of 15 to 25 cycles (250 ms to 416 ms). Section 8.3.4 suggests that a delay of 0.1 s should be adequate. However, the same paragraph emphasizes the need for time coordination to prevent tripping due to a system faults, while also warning that longer delays increase the risk of catastrophic bank failure [2]. Furthermore, The guide, in Table 1, specifies that fast operation is required to minimize damage during rack-to-rack faults.

In response to these events, some utility companies where expressed concern about increasing the delay time of the ANSI 46 protection for SCB. Others, after these events, implemented delays ranging from 0.7 s to 2 s. It became evident that more thorough understanding of the issue was necessary. Additionally, some utilities chose not to enable the ANSI 46 protection function in their SCB.

III. Problem Statement

The critical issue concerning the application of the ANSI 46 protection function for high-voltage SCB is the determination of and adequate delay setting, which is intrinsically dependent on the backup protection systems of the adjacent elements, all while minimizing potential damages to the SCB. Several key questions have emerge following the undesired operations of the ANSI 46 protection:

- Under what conditions is the ANSI 46 protection function required for SCB?
- Is the unbalance neutral current protection ANSI 60N enough for a rack-to-rack faults?
- What is the risk of a rack-to-rack fault occurring within a high-voltage SCB installation?
- What are the primary causes of rack-to-rack faults in high-voltage capacitor banks? To what extent can rack-to-rack faults be attributed to deficiencies in the design or effectiveness of bird countermeasures for high-voltage SCB?
- What is the optimal delay of the ANSI 46 protection function in high-voltage SCB?
- Is coordination necessary to prevent SCB disconnection due to the remote operation of a breaker failure protection (ANSI 50BF)?

- How can the operational reliability of the ANSI 46 protection function in SCB be enhanced?

IV. State of the Art

A well-designed and implemented capacitor bank (SCB) protection system is critical, beginning with a robust design phase where adequate protection schemes are established to prevent operational issues and mitigate the destructive effects of possible faults, including rack faults [3].

Negative-sequence current protection elements have been available for several decades, offering considerable benefits for detecting unbalance conditions [4]. A key challenge for modern protection engineers is the need for diligent verification of protection function applications. The IEEE C37.99-2012 guide [2] provides recommendations alongside corresponding warnings, as previously discussed. They are summarized as follow:

- Section 7, Introduction to bank and system protection, table 1, rack-to-rack flashover, *"Phase overcurrent or negative sequence relay: unbalance current for wye-wye capacitor banks, Fast operation is required to minimize damage. See 7.1.4 and 7.1.5"*
- Section 7.1.15 Protection for rack faults (arc-over within the capacitor rack). It gives clear warning: *"but tripping should be delayed to coordinate with the other relays in the system"*. It provides the standard criteria: A setting of 10% considering the maximum system voltage unbalance and capacitance variations. About the delay it gives a range and another warning: *"delay setting of 15 to 25 cycles, may provide adequate coordination for faults external to the bank"*.
- Section 8.3.4 Unbalance trip relay considerations. It gives another warning *"The unbalance trip relay should have enough time delay to avoid false operations due to inrush system ground faults, switching of nearby equipment"*. It gives another reference time of 0.1 s but as well another big warning: *"For unbalance relaying systems that do not compensate for system unbalance and may be therefore operate on a system voltage unbalance (ground fault) time coordination with upstream protection is required to avoid tripping due to a system fault. However delays increase the probability of catastrophic bank failure"*

Established methods exist for calculating protection settings in capacitor banks, encompassing a variety of techniques, including unbalance overcurrent and voltage protection functions [5]. Notably, system unbalance does not have an effect on neutral unbalance double-wye ungrounded capacitor banks [6]. Furthermore, voltage-based methods for detecting unbalance conditions can offer faster response times compared to overcurrent methods, potentially mitigating catastrophic damages [7]. Multiple approaches for implementing unbalance protection in capacitor banks are documented in the literature [8, 9].

It was found that several references of high-experience field experts have issued warnings regarding the coordination of unbalance protection in SCB with respect to both line and system faults. For instance, reference [10] estates that, *"unbalance elements respond to line and system faults, requiring long coordinating time delays"*.

Based on the authors' experience, the probability of a rack-to-rack fault in high-voltage SCB decreases as the nominal voltage of the SCB increases. This is attributed to the greater electrical distance resulting from the phase-to-phase distance insulation coordination requirement [11]. Furthermore, reference [12] suggests that faults caused by birds are not common. According to [13] series faults are the most common faults in SCB, and when birds produce faults in high-voltage SCB, for example, in 500 kV as [14] explains, bird nesting causes series mode faults.

Rack faults can be exceptionally destructive due to the energy stored within the capacitors. Several decades ago, reference [15] highlighted the difficulties of detecting unbalance conditions and the associated problems of the rack fault damages, while recommending a time delay of 0.5 seconds for unbalance protection functions.

In Colombia it was a common practice that for double-wye ungrounded SCB, the neutral current transformer with the function ANSI 60N and the function ANSI 46 are the protection functions for protecting the SCB during unbalance abnormal [16] or fault conditions.

Finally, another aspect that is very relevant about the current practices observed by the authors is that modern protection studies are based on short-circuit studies carried out by modern simulators. All the protection studies in Colombia received for high-voltage SCB do not have a simulation of unbalance conditions of the SCB. The reason is that most simulators do not offer a detailed internal model of the SCB, and its representation is made by just concentrated parameters of the SCB that is a suitable model for external and bay faults only. Additionally, traditional practices are derivative in field measurements of the normal operation unbalance conditions, and they normally do not consider the maximum unbalance condition for external faults.

V. Analysis of the Problem with an EMT Real Reference Model

After the aforementioned real-world events, XM S.A. E.S.P, the operator of the Colombia power system, developed an EMT model based on one of the events affected grid. Fig. 4 illustrates the topology of this real reference model, which includes a 20 Mvar capacitor bank in a 110 kV substation. The faults points considered in this model encompassed external faults at the remote substation and rack-to-rack faults within one of the wye-connected sections of the SCB.

The EMT model was developed using ATPDraw 6.3, and it included the representation of each capacitor cell according to the real topology of the SCB. The protection system was simulated, including overcurrent protection functions using available relays, incorporating some modifications. Additionally, new blocks were created using the EMTP/ATP modeling simulation language (MODELS) to simulate the ANSI 46 function and other possibilities that were further analyzed. The circuit breaker and tripping bus were

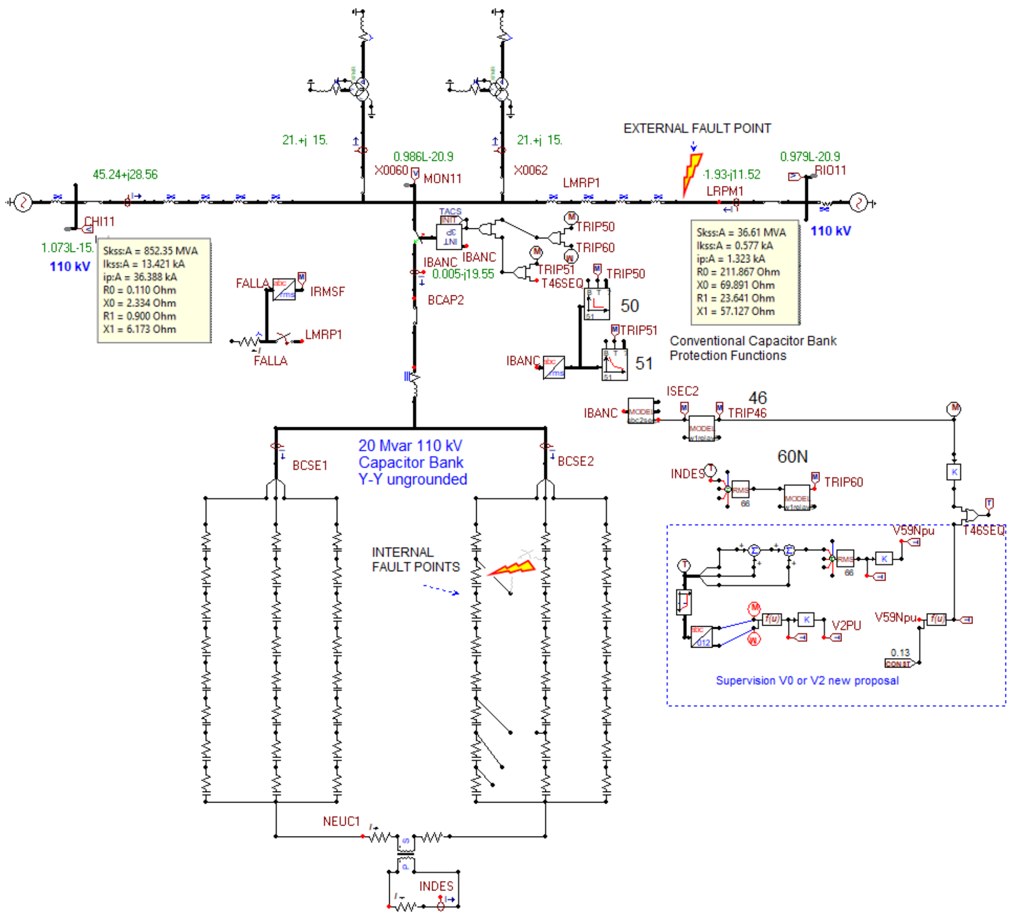

Fig. 3. ATPDraw model of the 110 kV reference grid

implemented using a combination of the Transient Analysis of Control Systems of the EMTP/ATP (TACS) and MODELS. Fig. 3 shows the model in ATPDraw.

Table II details the overcurrent protection settings applied to the capacitor bank in the reference model within the relay R1.

TABLE II
OVERCURRENT PROTECTION SETTINGS OF RELAY R1 OF THE CAPACITOR BANK OF THE REFERENCE MODEL

Function	I pickup [A]	Type	Time or dial [s]
50	800	Defined Time	0.1
51	131.2	Curve IEC NI	0.05
60N	1	Defined Time	0.4
46	10	Defined Time	0.2

Several fault types were simulated at the designed fault locations to understand the behaviors of the electrical variables and t he operational conditions of the ANSI 46 protection function during both internal and external fault events.

In Fig. 5 it can be observed that, during an external fault simulation, the ANSI 46 function is tripped before practical Zone 2 time delay (300-400 ms) or any overcurrent protection within the line bay (relay R2, 500-600 ms). This condition reflects a miscoordination, consistent with what was observed in the events. The simulation confirmed that this behavior was not due to a malfunction of the capacitor bank bay relay.

Fig. 6 illustrates the currents behavior for an internal rack-to-rack fault occurring at the 50% of the column within one wye-connected section of the capacitor bank. Based on the observed currents and the tripping of the ANSI 46 protection functions, as anticipated, it can be concluded that:

- The ANSI 46 protection function is required to clear a rack-to-rack fault because the ANSI 60N protection function will not operate effectively to this type of fault [17].
- At the fault inception, a high-magnitude, transient fault current is generated. This high-energy transient can not be adequately managed by overcurrent protection functions alone and instead should be partially cover by the inherent short-circuit dynamic capacity of the equipment as a design consideration.
- Give the high energy (peak current) characteristic of a rack-to-rack fault, careful design consideration are paramount to mitigate potentially catastrophic consequences through robust design and appropriate protection schemes.

It is very clear that it is necessary to make more secure the operation of the ANSI 46 protection function if fast tripping is desired. With the focus on the double-wye ungrounded SCB, this work tested to supervise (blocking if higher than) the function ANSI 46 with residual voltage (3V0) and negative

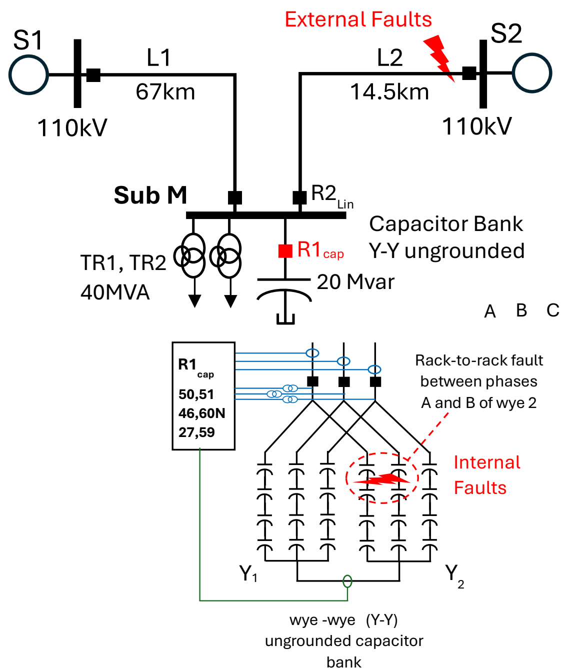

Fig. 4. Reference Grid for presenting the problem and the possible solutions with external fault and internal rack-to-rack locations

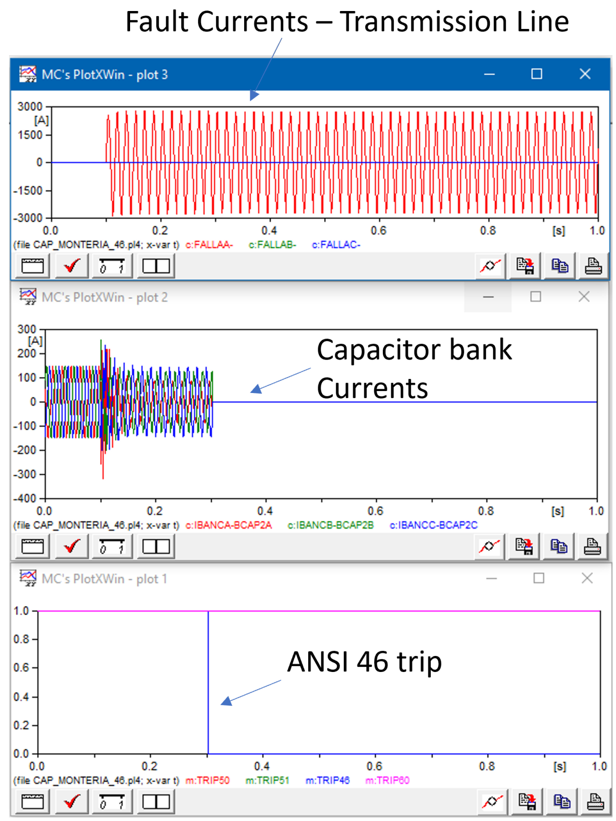

Fig. 5. Variables of 20Mvar capacitor bay for an external single-phase-to-ground fault - Reference grid

sequence voltage (V2) quantities with a value of 0.13 p.u. according to the behavior of the variables in the reference grid. Faults rack-to-rack were done close to the SCB bay (12.5% of the column from the bay) in order to generate more voltage unbalance.

Supervision of the ANSI 46 protection function with residual voltage, will work for any fault involving ground (because residual voltage is present) as it can be seeing with the supervised function T46SEQ signal in Fig. 7 for external faults, and in Fig. 8 for internal rack-to-rack fault. The problem of the supervision with residual voltage are phase-to-phase faults that they do not produce residual voltage to block the function as it can be observed in Fig. 9.

To avoid the problem with residual voltage for external phase-to-phase fault supervision with negative sequence voltage can be considered and it can work as the Fig. 10 and the Fig. 11 show for external and internal faults, considering the supervise function T46SEQ signal.

Results of these simulations are indicative of a possibility that it should be explored further and not as a final conclusion because there are many variables involved, including SCB topologies and power system parameters.

VI. Recommendations

In general, from the point of view of the power system operator, the recommendations based in this work are:

- Independent of the voltage level, time delay, and threshold of the SCB unbalance protection, they have to be determined for each case considering the electrical conditions analysis and the coordination with the backup protection system of the adjacent elements.
- When the backup protection systems of the adjacent elements are based on overcurrent protection functions or no pilot-protection schemes are used, a limitation of the remote clearing time will require a longer delay and margin between SCB overcurrent unbalance protection functions and the backup protection system of the adjacent elements.
- SCB specifications should comprehensively address operational ranges and ensure adequate withstand capacity in both current and voltage [18].
- Re-evaluate ANSI 46 settings to prevent miscoordination, in general the minimum delay time should be restricted to external protection operating times for fault at the remote substations including all protection functions, for example zone 2 (if not pilot-protection is available), breaker failure (50BF). Equation (1) shows the delay proposal in seconds.

$$Tdelay46 = max(remote\,fault\,clearing\,times) + 0.1 \quad (1)$$

  As a reference in Colombia ANSI 46 protection function for high-voltage SCB is now not recommended below 0.6 seconds.
- In SCB with a high risk of rack-to-rack faults, implement a supervisory function for ANSI 46 during external faults, explore voltage-based unbalance protection for faster fault detection, conduct detailed coordination studies, emphasize short-circuit dynamic capacity in

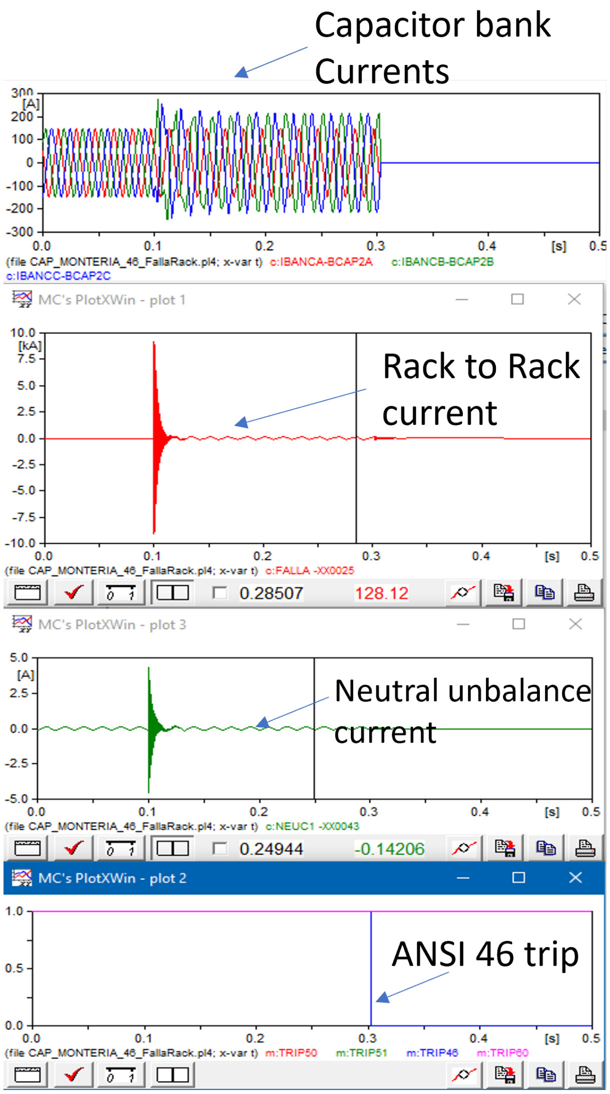

Fig. 6. Variables of 20Mvar capacitor bay for an internal 50% rack-to-rack fault - Reference grid

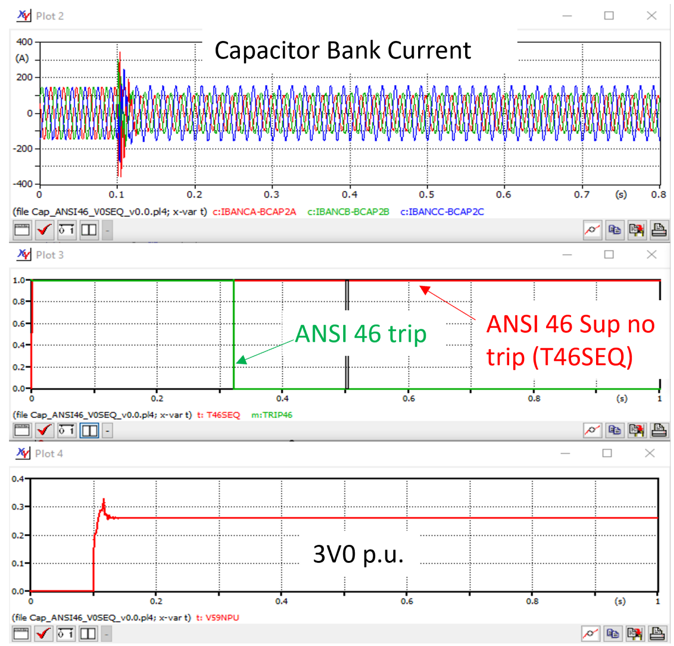

Fig. 7. Variables of 20Mvar capacitor bay for an external single-phase-to-ground fault with ANSI 46 supervision with residual voltage

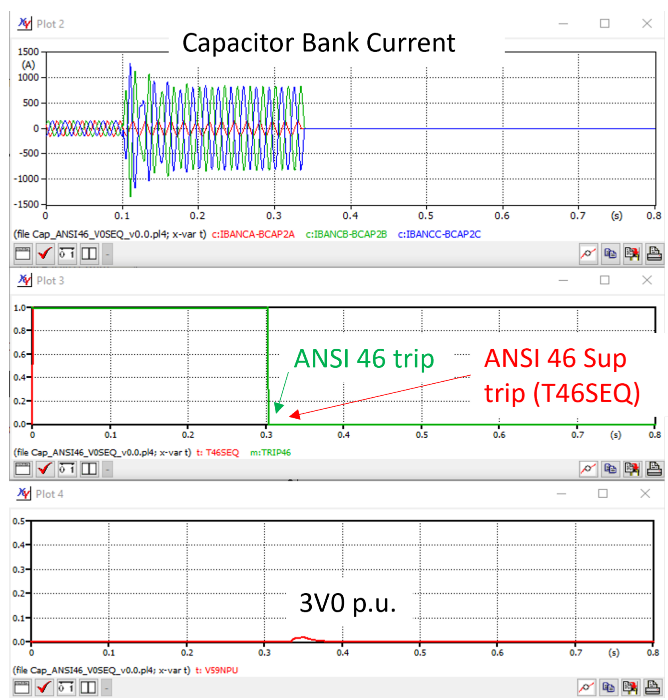

Fig. 8. Variables of 20Mvar capacitor bay for an internal rack-to-rack fault with ANSI 46 supervision with residual voltage

capacitor bank design, mandate thorough verification of protection settings, and develop more specific guidelines for protection settings based on real-life experiences.

- When performing or revising protection studies of SCB a detailed verification should be requested with a detailed EMT model that supports as well the COMTRADE files generation for the testing of the protection system of the SCB including internal and external faults.

VII. Future Work

This paper calls for manufacturers to analyze options for enhancing the speed and security of current based unbalance protection in capacitor banks, including the incorporation of supervisory functions, optical arc flash detection [19, 20], or the application of time-domain quantities with impedance principles [21, 22].

Furthermore, this study emphasizes the importance of well-designed shunt capacitor banks, noting that the risk of rack-to-rack fault in high-voltage SCBs can be mitigated through proper electrical clearances, exceeding basic insulation requirements. Finally, the scarcity of reliable statistics on SCB failures in MV and HV applications underscores the need for further data collection in this area.

Network simulation software companies should consider how to make it practical to have a method to simulate internal faults in SCB including rack-to-rack faults in order to verify

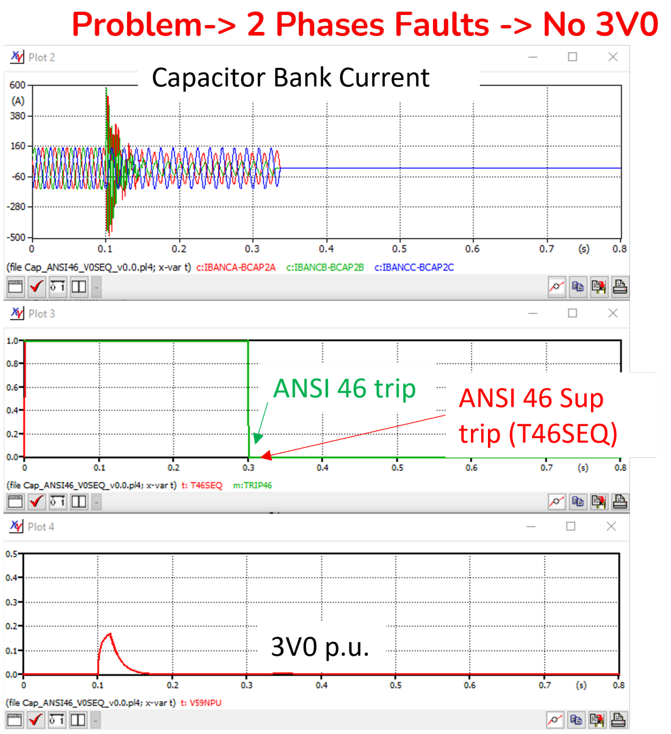

Fig. 9. Variables of 20Mvar capacitor bay for an external double-phase fault with ANSI 46 supervision with residual voltage problem

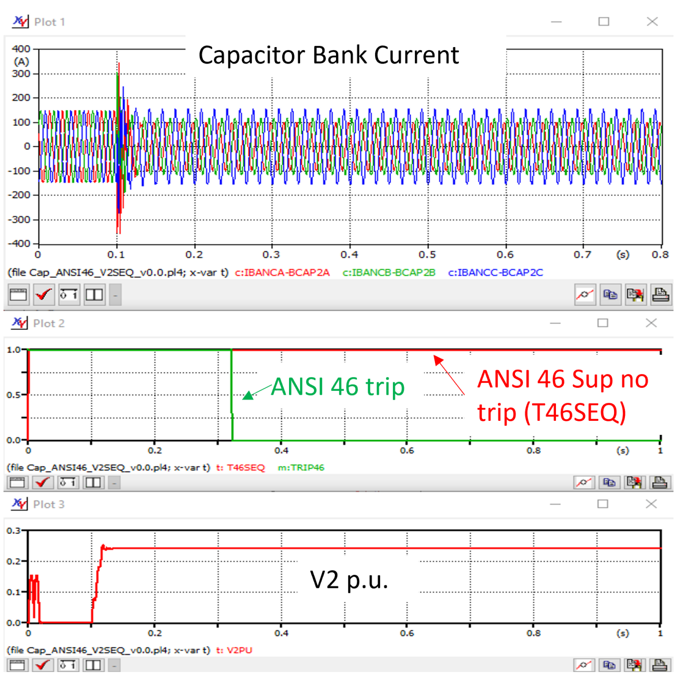

Fig. 10. Variables of 20Mvar capacitor bay for an external double-phase fault with ANSI 46 supervision with negative sequence voltage

properly all the protection functions of the protection system of the SCB.

VIII. Conclusions

The unbalance protection of shunt capacitor banks requires a detailed review to ensure proper coordination, specially for

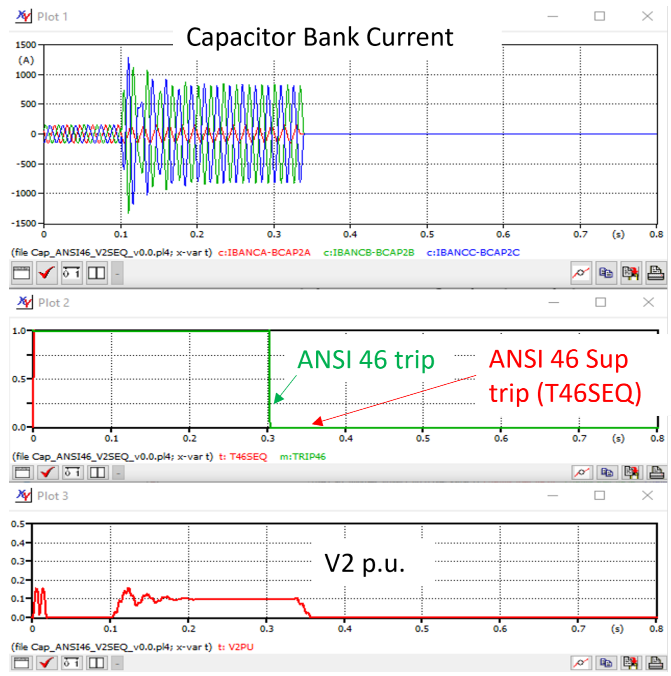

Fig. 11. Variables of 20Mvar capacitor bay for an internal rack-to-rack with ANSI 46 supervision with negative sequence voltage

external faults. This coordination should also consider the protection schemes available for adjacent elements and the operation of circuit breaker failure protection at the remote substations. Besides, testing of protection systems should include scenarios that simulate external faults with backup clearing times.

EMT simulations are a crucial component of protection analysis. Due to the new capabilities of modern protection relays, it is essential to conduct thorough analysis to verify protection coordination when incorporating new quantities, schemes, or logic into protections strategies.

Protection guides and technical documents are indispensable resources for protection engineers. A comprehensive understanding, achieved through rigorous study instead of selective readings, is essential to prevent misinterpretations and mitigate the operational risk. Consequently, the authors advocate for the technical community to prioritize a full and detailed study of guides and technical papers.

IX. Acknowledgment

The authors gratefully acknowledge their leadership for supporting this analysis and practical research based on real cases, and for encouraging the application of EMT simulation in real-event analysis and protection studies.

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According to The North American Electric Reliability Corporation (NERC) State of Reliability Reports [1], incorrect protection settings remain a leading cause of protection misoperations, as evidenced by power system event statistics. The loss of SCB during external faults in a power system directly impairs voltage stability, and this can increase the magnitude of a blackout if voltage stability is compromised. Furthermore, because a tripped SCB requires a discharge period (usually 10 minutes), before it can be reconnected, the impact on voltage stability can extend over several minutes or even hours.

When faults in transmission lines are cleared with a delay or by backup protection schemes a scenario more prevalent in sub-transmission systems SCB become more susceptible to protection miscoordinations due to undesired premature tripping of some specific protection functions.

This work presents a discussion on the performance of the ANSI 46 unbalance negative sequence current function when applied to high-voltage SCB. The analysis is motivated by instances of undesired tripping observed in the Colombian sub-transmission power system. A further review and discussion, supported by EMT simulations of a real-case scenario, examines the criteria recommended by the IEEE C37.99 guide [2]. Several recommendations and consideration are given regarding the application of the guide's recommendations to increase the security of the operation of SCB.

II. Undesired Events of the ANSI 46 Protection Function in Shunt Capacitor Banks in Colombia

Between 2016 and 2017, four events occurred within the Colombian power system, specifically in the sub-transmission portions of the grid (110 kV and 115 kV), involving ~~early~~ unintended disconnection of SCB during external faults due to the activation of the ANSI 46 protection function.

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