Measurements and Simulations in the Analysis of Transformer Failures during Vacuum Circuit Breaker Switching and Surge Protector Applications

N.C. Jesus, B.D. Bonato, R. Torquato, J.R. Cogo, L.M. Duarte, A.M. Laurentino; G.R. Santos

Abstract— **This paper presents the results and expertise achieved during the monitoring and initial root cause diagnosis of systemic failures in dry-type transformers, which occurred during energization switching of vacuum circuit breakers (pre-strikes). Measurement results obtained during the fault investigation were utilized to effectively confirm the root cause and evaluate the performance of surge protectors. Measurements from 34.5 kV installations without any protection will be presented, as well as real cases involving the application of RC-type surge suppressors and, more recently, a practical application using only surge capacitors. A historical qualitative comparison was conducted, considering results from various measurements in industrial electrical systems. Simulation results, derived from the implementation of a vacuum circuit breaker model in the system using the electromagnetic transients program ATP, will also be presented.**

Keywords: **Vacuum Circuit Breakers, Dry-Type Transformers, Measurements, Transients, Pre-Strikes, Restrikes, Surge Protectors, Simulations.**

I. Introduction

VACUUM circuit breakers exhibit arc extinction characteristics and capabilities that make them viable and efficient, especially for medium-voltage electrical systems. In recent years, with the need to reduce environmentally harmful greenhouse gases, vacuum technology for high-voltage systems has been developed [1], [2], along with other types of alternative gases [3]. Consequently, an expansion in the scope of vacuum circuit breakers (VCB) is anticipated. However, the switching of these devices during operations can result in transient overvoltages, increasing the stress on transformer windings and heightening the risk of equipment failure. This paper presents the main concepts related to switching overvoltages caused by vacuum circuit breakers, which are widely used in various applications. Currently, more than 80% of new medium-voltage installations employ vacuum arc extinction circuit breakers [4]. Overvoltages associated with breaker switching have been observed for many years in the operation of electrical systems.

Several operational issues have been attributed to a significant number of transformer failures involving circuit breaker switching operations [5], [6]. Generally, these transformer failures share relatively common parameters and characteristics, such as the application of vacuum circuit breakers or, less frequently, SF6 circuit breakers, short cables or busbar connections, and applications primarily involving 34.5 kV operating voltages and dry-type transformers. In Brazil, starting in early 2013, several consecutive transformer burnouts occurred, marking a national milestone in the application of dry-type transformers in pulp and paper production industries, as reported in [6]. Since then, studies and simulations of electromagnetic transients involving circuit breaker operations have been recommended to guide the definition and installation of surge protectors. To provide a temporal assessment, the results of measurements during vacuum circuit breaker operations in industrial systems will be described, considering systems that experienced failures and systems equipped with surge protectors, including a snubber (RC) type and another with only surge capacitors (SC).

An illustrative example highlighting the current relevance of this type of study will be presented, along with the analysis results of a 34.5 kV system's performance modeled using the ATPDraw electromagnetic transient simulation program.

Simulations of energization (pre-strike) and de-energization (restrike) switching operations were conducted, analyzing high-frequency events to define the level of protection and the configuration required to mitigate transient overvoltages. This type of analysis is strongly recommended for systems equipped with vacuum circuit breakers and dry-type transformers, especially those operating at 34.5 kV, necessitating verification of the protection installation.

II. Switching Overvoltages Of Circuit Breakers

Overvoltages can be classified based on their waveform and duration. In this analysis, transient overvoltages related to vacuum circuit breakers during switching of transformers under no-load conditions and harmonic filters will be presented.

N. C. Jesus is a graduate student with UNIFEI - Federal University of Itajubá and is with GSI Engenharia e Consultoria Ltda, Rua Mato Grosso, n°120, ZC: 12062-120, Taubaté-SP, Brazil (nelson@gsiconsultoria.com.br).
B. D. Bonato is with UNIFEI - Federal University of Itajubá, Av. BPS, n°1303, ZC: 37500-903, Itajubá-MG, Brazil (bonatto@unifei.edu.br).
R. Torquato is with UNICAMP - University of Campinas, Av. Albert Einsten, n°120, ZP: 13083-852, Campinas-SP, Brazil (torquato@ieee.org).
J. R. Cogo is with GSI Engenharia e Consultoria Ltda, Rua Mato Grosso, n°120, ZC: 12062-120, Taubaté-SP, Brazil (gsi@gsiconsultoria.com.br).
L. M. Duarte is with GSI Engenharia e Consultoria Ltda, Rua Mato Grosso, n°120, ZC: 12062-120, Taubaté-SP, Brazil (marlus@gsiconsultoria.com.br)
A. M. Laurentino is with GSI Engenharia e Consultoria Ltda, Rua Mato Grosso, n°120, ZC: 12062-120, Taubaté-SP, Brazil (ahmad.laurentino@unesp.br)
G.R. Santos is with GSI Engenharia e Consultoria Ltda, Rua Mato Grosso, n°120, ZC: 12062-120, Taubaté-SP, Brazil (grsantosv1@gmail.com)
Paper submitted to the International Conference on Power Systems Transients (IPST2025) in Guadalajara, Mexico, June 8-12, 2025.

The main types and characteristics of events involving switching overvoltages are discussed, considering de-energization and energization conditions of vacuum circuit breakers [4], [7], [9].

A. Current Chopping

In an ideal system, circuit breakers interrupt the current exactly at the natural zero crossing. However, when a relatively small current is interrupted by a circuit breaker, the action of the internal arc suppression devices can cause the current to be abruptly and prematurely brought to zero before its normal zero crossing. This phenomenon, known as “Current Chopping”, is a form of current suppression that can lead to overvoltages due to the magnetic energy stored in the equivalent circuit. This condition can occur naturally when the current from a reactor or transformer (magnetizing current) is interrupted by the circuit breaker. The value of the chopping current is typically considered to be in the range of 2 to 6 A [7]. This parameter is highly relevant in the modeling of circuit breakers under multiple reclosing conditions after breaker operations. In this study, based on the measurements, a maximum chopping current of 3 A was considered.

B. Multiple Reignitions (Restrike)

In switching operations of small inductive or capacitive currents, high overvoltages can be generated if arc reignition occurs after the first current interruption and if the switching device is capable of interrupting high-frequency transient currents, which establish themselves after reignition events. This process always includes a transient relationship between the system capacitances and the load side. If this process occurs repeatedly, it is defined as multiple reignitions. The amplitudes tend to increase with each reignition, and with the escalation of voltage, severe overvoltages raise the risk to both operation and equipment [4], [7], [8].

C. Virtual Current Chopping

This phenomenon can occur during the interruption process of switching devices due to the dispersion between the poles of the three-phase system. This type of event is strongly dependent on the system parameters and is rarer than the other events previously presented [4]. During an opening operation, with the increase in voltage amplitudes caused by reignitions, high-frequency overcurrents are generated as a result. If this transient event is magnetically or electrostatically coupled, due to the parasitic inductances and capacitances of the system, the currents induced in the other phases will be suppressed. After the interruption of the first pole of the circuit breaker, the currents in the other phases, which still conduct the fundamental frequency components, will also contain superimposed transient currents in their waveforms. If the circuit breaker interrupts one of these high-frequency components, they will be referred to as “Virtual Current Chopping”. Compared to the current chopping phenomenon, the effects of chopping the induced currents may be more severe. The interruption of high-frequency currents, a typical characteristic of vacuum circuit breakers, can generate severe sequential overvoltages, especially in the case of motors.

D. Multiple Pre-Ignitions (Pre-Strike)

The events described earlier were directly related to overvoltage during circuit breaker opening operations. Unlike the others, this item addresses the transient overvoltages during closing operations. During the closing operation of a circuit breaker’s poles, the equivalent circuit is almost complete just before the final mechanical contact touch. Under these conditions, the system’s voltage forces a reduction of the "gap," creating an increase in dielectric stress between the contacts. If the voltage between the poles exceeds the breaker’s cold characteristic (dielectric breakdown voltage), pre-ignitions of the electric arc will occur, with the possibility of repetitive overvoltages [4], [9], [11].

III. Protection Against Transient Overvoltages

For the protection of equipment in electrical systems at risk of transient overvoltage events, traditional protection methods commonly used include surge arresters (SA), surge capacitors (SC), and surge suppressors, such as RC filters (Snubbers). Series inductors (Chokes) or even special transformers with surge arresters directly connected to their windings are other technical proposals for mitigation [7], [13]. It has been found that, in most cases where surge suppressors are applied, the preferred configuration is to install them as close as possible to the terminals of the equipment to be protected.

IV. Switching Measurements In Industrial Systems

Measurements were conducted during the monitoring of the first reported failures associated with the switching operations of transformers. The results presented in this paper were obtained through field measurements using transient event recording devices (1 MHz), installed on the secondary side of instrument transformers (ITs). Therefore, although the results are considered qualitative due to the unavailability of frequency response data from the measurement with voltage transformers (VTs), the obtained results clarify and show the trends and characteristics of some of the phenomena reported, despite the measurement using with low bandwidth, as possible in real situations. Fig. 1 presents an illustrative example of the measurement results of line voltages (phase-to-phase), obtained during the assessment of a medium-voltage system in an industrial installation, confirming the occurrence and behavior of multiple restrikes during the circuit breaker opening operation.

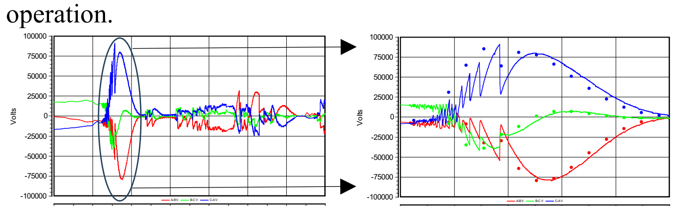

Fig. 1 Measurement results and details of overvoltages due to the occurrence of multiple reignitions (restrikes).

However, it is important to highlight that this specific event did not result in failures and there is no correlation with the actual locations of transformer failures. It was included only to show that transient measurements with power quality instruments can be essential in the analysis of events such as circuit breaker switching operations.

V. Characteristics of Electrical Systems

The electrical systems analyzed present similar concepts due to the paper and cellulose factory designs, with some of these transformers located at distances ranging from 20 to 400 meters from the circuit breaker cubicles.

At the beginning of the implementation, one of these projects faced a significant decision, with a change in the system configuration, adopting to the use of dry-type transformers instead of the traditional oil-immersed transformers. The basic single-line diagram where the failures began is shown in Fig. 2.

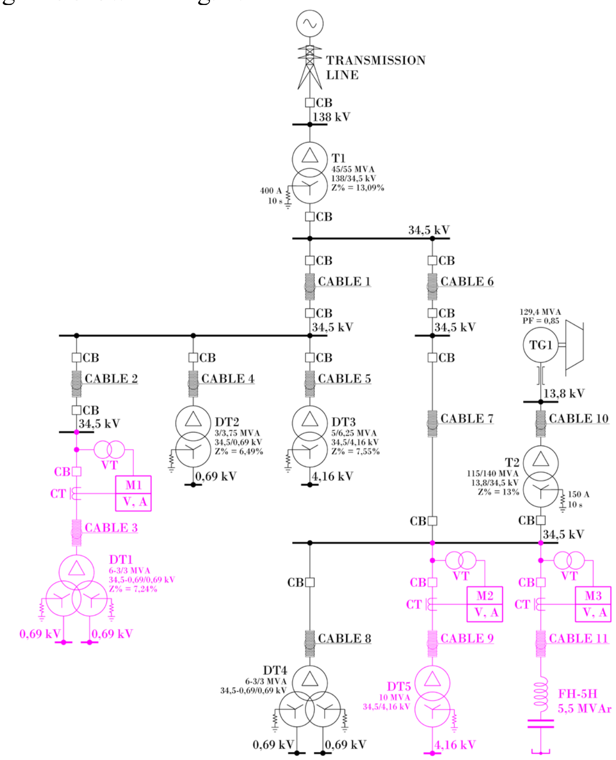

Fig. 2. Single-line diagram of the electrical system where systemic failures of dry-type transformers occurred.

Fig. 3 illustrates the details of the failures of two transformers from different manufacturers on the same site, showing short-circuits between the primary windings, side of 34.5 kV, referring to the 6 and 3 MVA transformers, respectively.

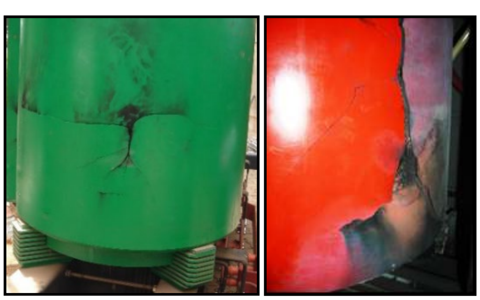

Fig. 3. Details of transformer failures during vacuum circuit breaker energization switching.

The initial analysis involved dry-type transformers with rated powers of 3, 5, 6, and 10 MVA, but the cases involving primarily 6-3-3 MVA transformers, which experienced a higher number of failures, will be presented.

Information was obtained regarding routine tests, parasitic capacitances, saturation curves, and, in a specific case, the frequency response in the SFRA (Sweep Frequency Response Analysis) test.

VI. Historical Measurement Results During Vacuum Circuit Breakers Operations at 34.5 kV

It should be noted that, in addition to the qualitative aspect of the measurements, the field test monitoring indicated the real operating conditions since the first historical failures occurred during the changeover of transformer types in industrial systems. In the initial project where dry-type transformers were first installed, systemic failures of various equipment occurred.

The analyzed characteristics pointed to switching operations as the cause, with gas-insulated switchgear (GIS) enclosures using vacuum circuit breakers, short cables, and dry-type transformers, especially at the operating voltage of 34.5 kV. Subsequently, surge arresters of the ZORC type were applied on an emergency basis. In a similar project, after identifying the root cause, surge protectors of kind RC (snubber) were also used, installed together with surge arresters. This type of protection became a design criterion and mandatory requirement for subsequent projects implemented after the first one, proving effective in protecting dry-type transformers.

Lastly, in one of these recent projects, only surge capacitors were used, and the results will be discussed later. Therefore, an ongoing assessment was carried out in industrial pulp and paper installations, which now use dry-type transformers in current projects, necessitating their transient protection. The results were obtained during the root cause identification phase, as well as the beginning and improvement of surge arrester application over approximately eight years. Some of these results will be presented as part of the experience and field measurement analyses.

As a crucial part of this analysis, several measurements were performed during tests and operations of vacuum circuit breakers installed in distribution panels, insulated with SF6. The initial evaluation of the oscillographs was used in an attempt to identify the root cause of the numerous consecutive failures of the dry-type transformers, but the relay sampling time did not contribute to this definition. Only with power quality measurements capable of detecting transient events (sampling rate of 1 MHz) and monitoring from the onset of historical failure occurrences, the systemic cause due to transient overvoltages was identified. These were correlated with vacuum circuit breaker operations inserted in GIS enclosures, connecting short cables to dry-type transformers. In two similar installations, failures occurred even with circuit breakers and transformers from different manufacturers.

A. *Identification of the Systemic Cause*

The systemic failures began between January 2nd and 3rd, 2013, when three dry transformer failures were observed in sequence during their energization operations. Still in the same year, dozens of failures of 34.5 kV dry transformers were reported, installed with vacuum circuit breakers, associated with GIS-type switchgears, with SF6 gas insulation.

All cases were linked at energization switching, and in some of these cases, the failure occurred during the first energization of the transformer.

Typically, overvoltages during circuit breaker opening operations, if restrikes occur, are expected to be more significant than those during energization switching.

In the commissioning measurements analyzed between 2013 and 2021, as well as other systems at 34.5 kV, with or without surge protectors, no signs of restrikes were detected from the busbar in any of these systems.

For the cases in this analysis, circuit breaker switching that resulted in transformer failures were linked to energization events, with the likely cause being the high rates of voltage growth (dv/dt) and excitation of frequencies near the resonance points within the transformer windings, exclusively due to the effects of pre-strikes, as can be evidenced in Fig. 4, which illustrates one of the measurement results in the 34.5 kV electrical system (M1 in Fig. 2).

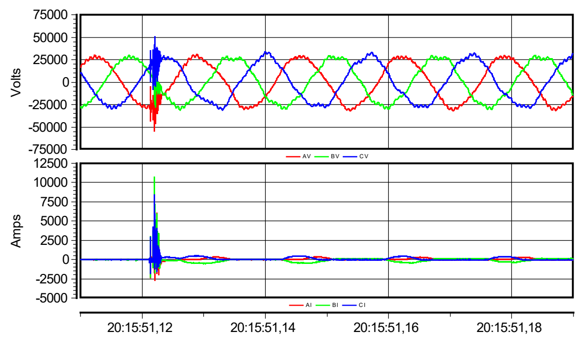

Fig. 4. Measurements of transformer energization (pre-strikes).

Fig. 5 illustrates the details of the transient events, with high currents during the pre-ignitions of the referred switching operation.

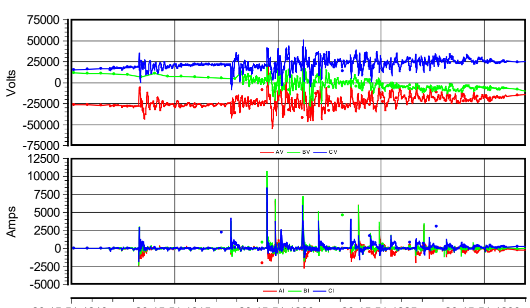

Fig. 5. Details of transient events during energization (pre-strikes).

Fig. 6 shows another transient event, also related to transformer energization, clearly indicating the effects of pre-strikes. An important detail is that, unlike most cases, high overvoltages were recorded, and high-frequency currents entered the initial region of the inrush currents (M2 in Fig. 2).

Fig. 7 shows the detailed transient event from Fig. 6, related to the switching of transformer energization, clearly indicating the repetitive effects resulting from pre-strike events.

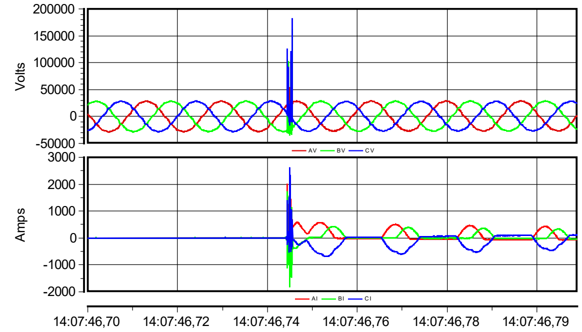

Fig. 6. Measurements of transformer energization (pre-strikes).

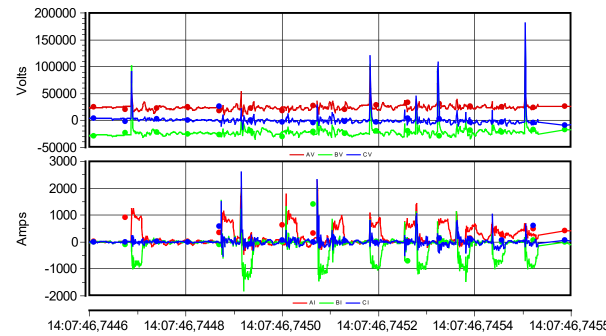

Fig. 7. Details of the transient events during transformer energization (pre-strikes).

Several transient overvoltages were recorded in the electrical system, with the results of the high rates (dv/dt) and imposed frequencies having a direct impact on the failures of the dry-type transformers. Additionally, as a complementary example, in the case of the energization of harmonic filters, the vacuum circuit breakers had two chambers in series, which also generated pre-strike type transients, as can be seen in Figs. 8 and 9, for the energization switching of a 5th-order harmonic filter in this system (M3 in Fig.2).

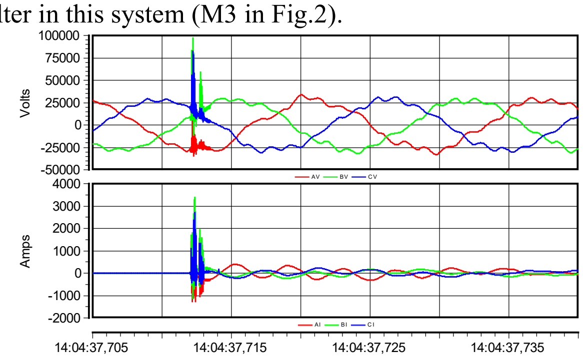

Fig. 8. Measurements of the energization of a 5th-order harmonic filter.

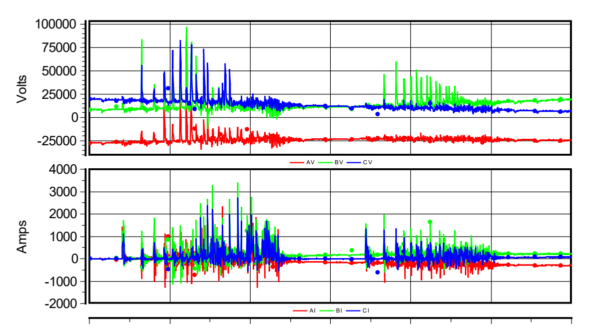

Fig. 9. Details of transient events during energization (pre-strikes).

B. Measurements of Switching with Surge Supressor

After completing two previous projects for large pulp and paper companies in Brazil, it was established as a design criterion the need to assess and specify surge arresters alongside the operation of dry-type transformers. Since then, this type of solution has been used for cellulose and paper company projects. Considering the impact of the systemic failures at the time, the initial energization of transformers was closely monitored as an important part of the commissioning of the surge protectors (snubber). The configurations and meters used in the previous section were the same in this scenario, with surge protectors using RC filters (Snubbers) in conjunction with surge arresters. The results of energizations with transformers installed with snubbers are presented. Fig. 10 shows the result of the measurement of the first energization of a 6 MVA dry-type transformer (DT1 in Fig. 2) after the implementation of a project with about 60 transformers, all equipped with surge arrester and snubber (RC Filter), where values of R = 33 Ω and C = 0.2 µF were adopted. The effects of traveling waves from the cables were initially observed during the first switching, followed by the subsequent action of the surge suppressor.

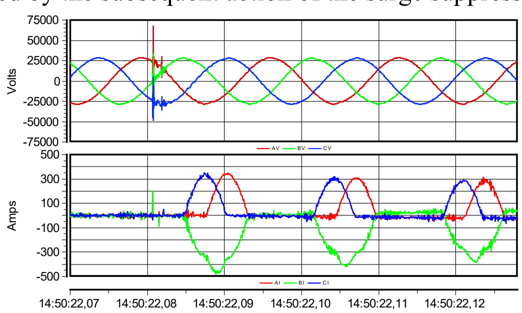

Fig. 10. Measurements of the first energization with surge suppressor (RC).

After this first operation, the remaining transformers, all equipped with surge suppressors, were energized, showing a greater tendency to reduce transient overvoltages as more suppressors were also energized, as shown in Fig. 11 for the energization of a 10 MVA transformer (DT5 in Fig. 2). All equipment was energized without failures related to transient overvoltages due to the widespread application of surge suppressors of the (RC) type (snubber).

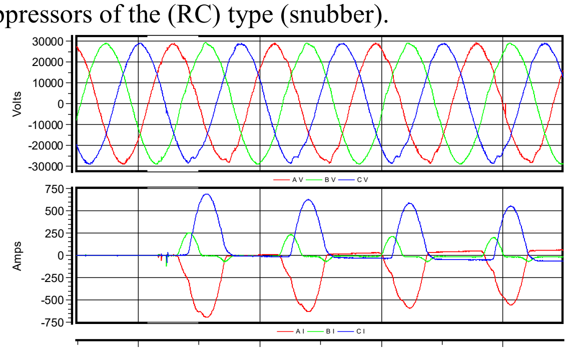

Fig. 11. Measurements of energization with surge suppressor (RC).

C. Measurements of Switching with Surge Capacitors

In 2021, with the startup of a new industrial plant in the same pulp and paper sector, using dry-type transformers at 34.5 kV, a new monitoring process was carried out. This time, the proposed solution for protection against transient overvoltages during switching operations did not use the RC filter solution (snubber), but only surge capacitors with a value of 0.05 µF, installed on the 34.5 kV side. Transient variations were observed during measurements of a total of 31 transformer switching operations, with ratings of 2, 3, 4, 6, and 10 MVA, which also did not present any failures resulting from the switching operations. Fig. 12 illustrates one of the results from the switching measurements of a 6-3-3 MVA transformer.

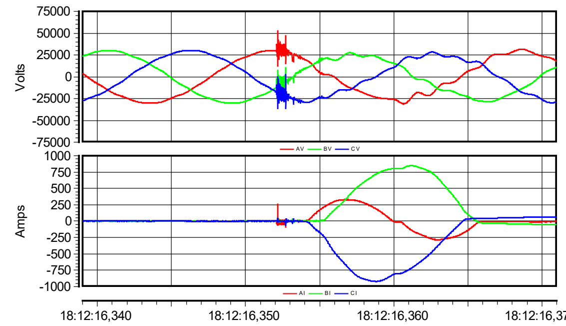

Fig. 12. Measurements of energization with surge capacitors (CS).

VII. Modeling of the Electrical System

Simulations were carried out using a vacuum circuit breaker model implemented for transient analysis, based on the comparisons presented in [9], [11], [13], [14]. The base circuit used in the ATPDraw program for model validation is shown in Fig. 13.

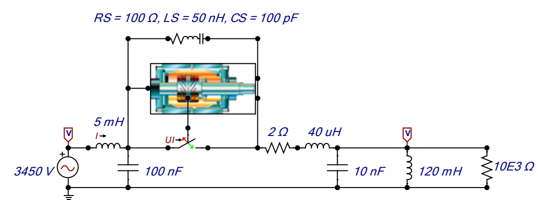

Fig. 13. Implementation of the vacuum circuit breaker model in the ATPDraw.

For the implementation of the three-phase circuit breaker model, a routine was developed in the MODELS language, considering controlled switches of type 13 in ATP. In the vacuum circuit breaker modeling, Eq. (1) was used as the basis for the opening condition and possible re-ignitions (restrikes) [9], [11].

$$\mathrm{UB_{OP}} = A\,(t - t_{OP}) + B \tag{1}$$

Regarding the high-frequency current interruption capacity (quenching current), it is defined by the slope of the current that was restored through reignition, which also exhibits time-dependent behavior. Eq. (2) can be used to describe the characteristics related to the high-frequency current quenching capacities.

$$\frac{di}{dt} = C\,(t - t_{OP}) + D \tag{2}$$

For energization switching (pre-strike) [12], Eq. (3) can be adopted for the disruptive voltage, and Eq. (4) can be used for the high-frequency current quenching capacity.

$$\mathrm{UB_{CL}} = VM - A\,(t - t_{CL}) + B \tag{3}$$

$$\frac{di}{dt} = E - [C\,(t - t_{CL}) + D] \tag{4}$$

where:
UB_{OP} - Dielectric withstand of the circuit breaker during opening (V);
UB_{CL} - Dielectric withstand of the circuit breaker during closing (V);
A - RRDS - Rate of Decrease of Dielectric Strength (V/s);
B - Initial dielectric withstand voltage (V);
t - Time variable (s);
t_{OP} - Contact opening time (s);
t_{CL} - Contact closing time (s);
di/dt - Arc current extinction capability of the high-frequency (A/s);
VM - Maximum dielectric withstand voltage (V);
C - Constant related to the slope of the high-frequency current extinction capability (A/s²);
D - Constant related to the high-frequency current extinction capability (A/s);
E - Constant determined from the maximum value of the high-frequency current extinction capability (A/s).

For the simulations of the switching established in the system of the one-line diagram based on Fig. 2, data for the parasitic capacitances of the transformers and equipment, test impedances, saturation curves, surge arresters, and the representation of cables with distributed parameters were obtained, according to basic data presented in the appendix. The circuit breaker under analysis has a rated voltage of 40.5 kV, rated current of 1250 A, withstand short-circuit current of 40 kA and a basic insulation level of 200 kV. Table I presents the parameters used in the VCB modeling [7], [9], [11].

TABLE I
Parameters used in the vacuum circuit breaker modeling

Parameter	Unit	Opening	Closing
A	[v/s]	5.0×10^6	2.2×10^7
B	[v]	0.69×10^3	0
VM	[v]	-	6.0×10^4
C	[A/s²]	5.0×10^9	0
D	[A/s]	1.0×10^7	1.0×10^7
E	[A/s]	-	12×10^7

A. Switching Transformer with Pre-Strikes

This section presents the results obtained from the simulation of the transformer energization switching of 6- 3- 3 MVA, considering the occurrence of pre-ignitions, where the models with the dielectric characteristics of the circuit breaker and the equivalent parasitic capacitances, as provided by the manufacturers, were represented. Figures 14 and 15 show the transient voltages and currents resulting from the energization switching with the occurrence of pre-ignitions and multiple interruptions of the vacuum circuit breaker.

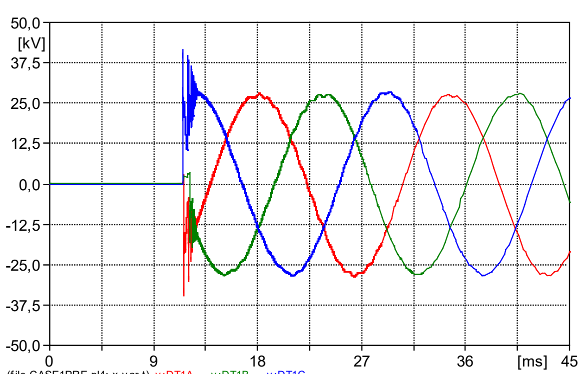

Fig. 14. Simulation of the transformer energization transient voltages.

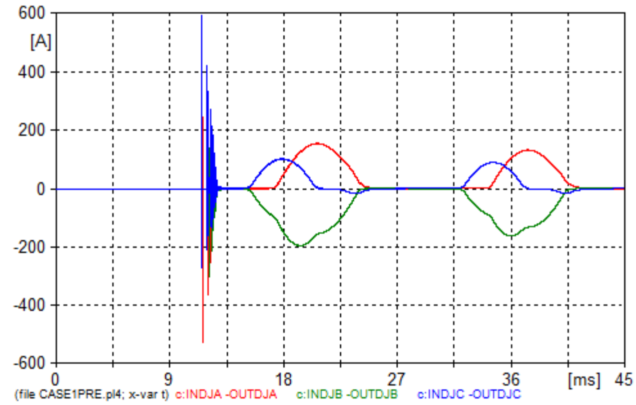

Fig. 15. Simulation of the transformer transient currents (pre-strike).

B. Switching Transformer with Restrikes

Fig. 16 shows the voltages and Fig. 17 shows the transient currents obtained during the simulation of the switch-off switching, with the occurrence of multiple reignitions, whose results are typical of the behavior of impulsive and repetitive overvoltages, related to occurrences of multiple reconductions after the circuit breaker opening.

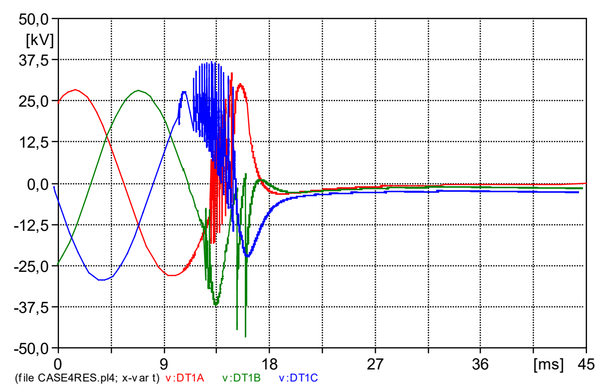

Fig. 16. Simulation of the transformer's transient voltages during turn-off switching (restrike).

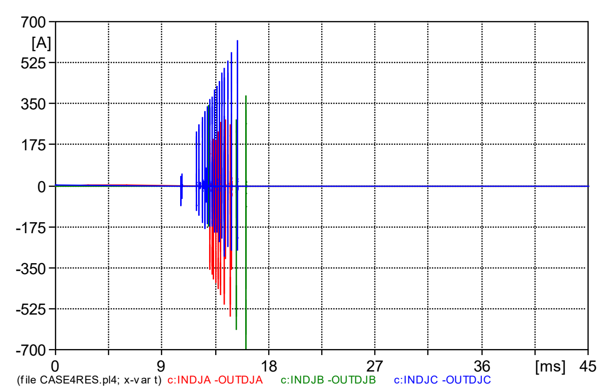

Fig. 17. Simulation of the transformer's transient currents (restrike).

C. Switching Transformer with Surge Supressors (RC)

For this item, surge protectors with the snubber type were included in the previous cases, with R = 60 Ω (twice the surge impedance of the cables) and a capacitance of 0.2 μF [6]. Fig. 18 shows the transient voltages during the simulation of the energization with the snubber, and Fig. 19 shows the results of the opening simulation with the same protection (RC), where in both cases, the overvoltages were reduced.

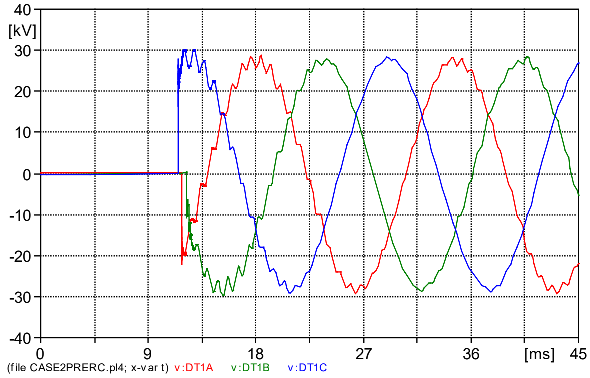

Fig. 18. Simulation of the transient voltages during transformer energization with snubber (R = 60 Ω and C = 0.2 μF).

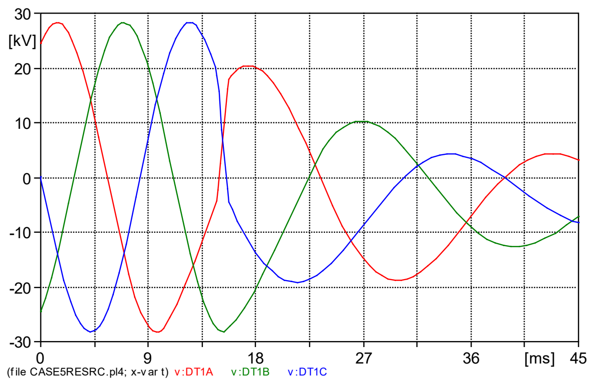

Fig. 19. Simulation of transient voltages during transformer de-energization with snubber (R = 60 Ω and C = 0.2 μF).

D. *Switching Transformer with Surge Capacitors (SC)*

Based on the values used in the field, a surge capacitor of 0.05 μF was also adopted at the terminals of the transformer under analysis.

Figs. 20 and 21 show the results with the use of capacitors only, corresponding to the energization and de-energization switching, respectively.

In the simulations of these cases, it was found that the use of the surge capacitor did not produce satisfactory results for the energization switching, even causing an increase in the number of pre-strike events, depending on its value and other parameters. In the case of restrikes, the effectiveness of the surge capacitor was confirmed, reducing all the reignitions.

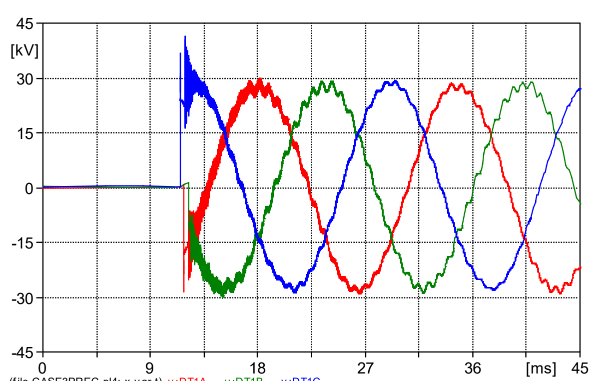

Fig. 20. Simulation of the transient voltages during the energization of the transformer with surge capacitor (SC = 0.05 μF).

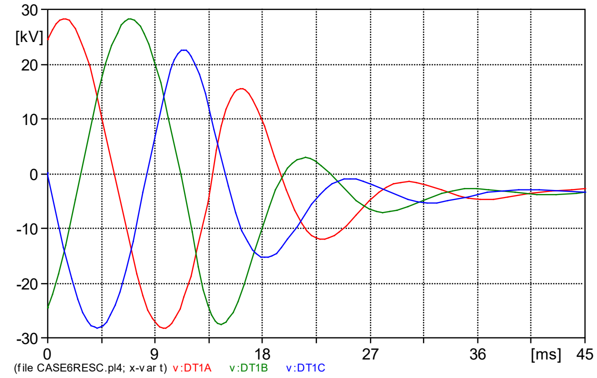

Fig. 21. Simulation of the transient voltages during the de-energization of the transformer with surge capacitor (SC = 0.05 μF).

VIII. Application Examples

Fig. 22 illustrates some recent practical examples that demonstrate the installation modes of surge suppressors (Snubber RC) for protecting dry-type transformers with operating voltages of 34.5 kV, against transient overvoltage resulting from vacuum circuit breaker switching, installed in industrial electrical systems [6], [10].

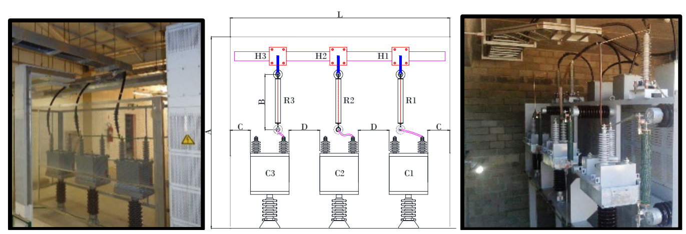

Fig. 22. Examples of surge suppressors installed for the protection of dry-type transformers at 34.5 kV.

In practical terms, the value of the resistor is initially defined based on traveling wave theory in terms of signal attenuation. First, the surge impedance of the cables that feed the transformer (ZC) is calculated, and normally the range used to specify the resistor used in surge suppressors comprises values between

$$ZC \leq R \leq 3\ ZC \qquad (5)$$

For the use of non-inductive resistors, the value of 33 Ω was defined as slightly higher than the surge impedance of the transformer cable and was applied in several installations. Additionally, the value of 60 Ω was used in another project, which adopted a value of 2 times the surge impedance of the cables. The values of the capacitors in series with the resistors are in the range of 0.1 to 0.5 μF, which can normally be found in the portfolio of surge capacitor manufacturers, facilitating their acquisition. Values such as 0.1, 0.2, 0.25, 0.3, and 0.5 μF are the most commonly used in practical situations.

Therefore, a sensitivity analysis must be carried out to define the final values based on system simulations. In both reported project cases where surge suppressors with 33 Ω and 60 Ω resistors were installed, 0.2 μF capacitors were used. It was found that a resistor with a value around 2 times the surge impedance presented better results for the analyzed case.

IX. Conclusions

This paper presented results related to systemic failures of dry-type transformers, where energization events resulting from vacuum circuit breaker operations were directly associated with insulation failures due to internal resonances. In the context of paper and pulp mills in Brazil, there was a significant shift in design practices with the replacement of oil-immersed transformers by dry-type transformers. During the initial energization switching in the commissioning phases, several failures were detected, with some transformers failing on their first energization, underscoring the impact of high dv/dt repetitive overvoltages. These findings were initially based on indirect measurements using voltage transformers (VTs) in GIS panel busbars. While the initial diagnosis relied on relay oscillography data, the root cause was not identified until transient recording devices with sampling rates up to 1 MHz were employed. Following this milestone, subsequent projects included recommendations for installing RC-type surge suppressors alongside arresters. Measurements and monitoring validated the effectiveness of these protective equipment.

Various transient overvoltages were recorded in the electrical system, which had a direct impact on the failure of dry-type transformers from two manufacturers.

These transient overvoltages frequently occurred during vacuum circuit breaker energization switching (pre-strikes), directly causing numerous transformer failures. This behavior, attributed to the combination of GIS panels, vacuum circuit breakers, and short cables, was confirmed through measurements. Simulations of the system using a vacuum circuit breaker model were also performed, assessing the performance of both RC snubbers and surge capacitors. While surge capacitors proved effective for disconnection switching, their overall efficacy was limited, suggesting the need for further evaluation. It is noteworthy that a new project from 2024, the company simply decided to return to using oil transformers, thus characterizing it as a relative setback.

Notably, during this period, transformer manufacturers likely improved their designs and insulation. In summary, to mitigate transient effects, particularly those related to pre-strike events, the use of RC filters emerges as the most suitable and effective solution for such applications.

Finally, we highlight that in practical terms, there is still a wide scope for research on this topic, about validating models and optimizing application techniques.

X. Acknowledgements

The authors acknowledge the financial support in part from UNIFEI - Federal University of Itajuba; UNICAMP - Universidade Estadual de Campinas; CAPES - Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil-finance code 001; CNPq - National Council for Scientific and Technological Development - Brazil; FAPEMIG- Fundação de Amparo à Pesquisa do Estado de Minas Gerais, under grant APQ-03609-17; INERGE - Instituto Nacional de Energia Elétrica. One author was funded by grant #2021/11380-5 from CPTEn - São Paulo Center for Energy Transition Studies; FAPESP - São Paulo Research Foundation.

XI. Appendix

Electrical System Data:

1) Source: 138 kV;

2) Short Circuit Impedance:
R0 = 14,44 Ω; X0 = 49,07 Ω; R1 = 5,65 Ω; X1 = 17,20 Ω;

3) Main Transformer T1:
Rated Power = 45 MVA;
Primary Rated Voltage = 138 kV;
Secondary Rated Voltage = 34,5 kV;
Percent Impedance= 13,09%

4) Cables: Cable 1: Cross Section: 500 mm^2; conductors per phase: 4; length: 650 m. Cable 2: Cross Section: 300 mm^2; conductors per phase: 2; length: 300 m. Cable 3: Cross Section: 240 mm^2; conductors per phase: 1; length: 25 m;

5) Distribution Transformer DT1:
Rated Power = 6-3-3 MVA;
Primary Rated Voltage = 34,5 kV;
Tertiary and Secondary Rated Voltage = 0,69 kV;
Primary to Secondary Impedance = 7,70% (3 MVA);
Primary to Tertiary Impedance = 7,70% (3 MVA);
Secondary to Tertiary Impedance = 15,40 % (3 MVA);

6) Parasitic Capacitances:
Capacitance between primary winding and ground = 420 pF;
Capacitance between secondary winding and ground = 1320 pF;
Capacitance between tertiary winding and ground = 1320 pF;
Capacitance between primary and secondary windings = 6.8 pF;
Capacitance between the primary and tertiary windings = 6.8 pF;
Capacitance between the secondary and tertiary windings = 11.5 pF;
Capacitance of panels (9 m) = 50 pf per meter = 450 pF.

XII. References

[1] X. Yao, J. Wang, S. Ai, Z. Liu, Y. Geng, and Z. Hao, "Vacuum Switching Technology for Future of Power Systems", Engineering, vol. 13, pp. 164-177, 2022.

[2] T. Heinz et al., "Why vacuum technology is not a simple scaling from medium to high voltage?", presented at the 30th Int. Symp. Discharges and Electrical Insulation in Vacuum (ISDEIV), Okinawa, Japan, 2023, pp. 100-106.

[3] CIGRÉ, A3 - Transmission and Distribution, "Current Interruption in SF6-Free Switchgear", Reference 871, 2022.

[4] A. Mueller and D. Saemann, "Switching phenomena in medium voltage systems - good engineering practice on the application of vacuum circuit-breakers and contactors", presented at the Petroleum and Chemical Industry Conf. Europe Electrical and Instrumentation Applications, Rome, Italy, 2011, pp. 1-9.

[5] D. D. Shipp, T. J. Dionise, V. Lorch, and B. G. MacFarlane, "Transformer Failure Due to Circuit-Breaker-Induced Switching Transients", *IEEE Transaction on. Industry Applications*, vol. 47, no. 2, pp. 707-718, Mar.-Apr. 2011.

[6] N. C. Jesus, J. R. Cogo, and L. M. Duarte, et al., "Modeling, simulation and analysis of switching transients for defining surge suppressors as transformer protection", presented at the XII CBQEE - Brazilian Conference about Power Quality, Curitiba, Brazil, Aug. 2017 (in Portuguese).

[7] S. Ghasemi, M. Allahbakhshi, B. Behdani, M. Tajdinian, and M. Popov, "Probabilistic Analysis of Switching Transients due to Vacuum Circuit Breaker Operation on Wind Turbine Step-up Transformers", EPSR - Electric Power Systems Research", vol. 182, May 2020, 106204.

[8] K. Trunk et al., "Small inductive current switching with high-voltage vacuum circuit breakers", presented at the 29th Int. Symp. Discharges and Electrical Insulation in Vacuum (ISDEIV), Padova, Italy, 2020, pp. 331-334.

[9] M. Popov, "Switching three-phase distribution transformers with a vacuum circuit breaker: analysis of overvoltages and the protection of equipment", Ph.D. Thesis, Delft Univ. Technol., Delft, 2002.

[10] J. R. Cogo, N.C Jesus, L. M. Duarte, et al., "Measurements of transformer energization switching considering the installation of surge suppressors", presented at the XI CBQEE - Brazilian Conference about Power Quality, Campina Grande, Brazil, Aug. 2015 (in Portuguese).

[11] B. Kondala Rao and G. Gajjar, "Development and application of vacuum circuit breaker model in electromagnetic transient simulation", presented at the 2006 IEEE Power India Conf., New Delhi, India, 2006, pp. 7.

[12] G. G. Bongiolo and L. C. Zanetta, "Integrated vacuum circuit breaker model for opening and closure switchings", presented at the 2018 Brazilian Symposium on Electrical Systems (SBSE), Niterói, Brazil, 2018, pp. 1-6.

[13] L. Liljestrand, E. Lindell, "Efficiency of Surge Arresters as Protective Devices Against Circuit-Breaker-Induced Overvoltages", *IEEE Transactions on Power Delivery*, vol. 31, no. 4, pp. 1562-1570, Aug. 2016, doi: 10.1109/TPWRD.2015.2501388.