Modeling and normative instructions for the application of EMT-based programs in the evaluation of medium voltage circuit-breakers in a real industrial system

M. L. Franco, M. S. Caetano, B. D. Bonatto, M. C. Passaro

***Abstract*—This paper aims to present a guideline for modeling and normative instructions for short-circuit (SC) and transient recovery voltage (TRV) analysis of medium voltage circuit-breakers installed in a real industrial system. The Alternative Transient Program (ATP) through its graphical interface ATPDraw was used in the work. The criteria used for modeling the analyzed industrial system are presented in detail. For a better understanding of the technical information required for the modeling employed in TRV and SC studies, a set of detailed and typical data used is presented in order to contribute to the reproduction of this case study in other expanding industrial power systems. The instructions for SC and TRV evaluation of circuit-breakers are based on the limits described by IEC standards and other references. The results are presented by discussing the effects of industrial expansion on the evaluated medium-voltage circuit breakers.**

***Keywords*—EMT, Industrial Systems, Medium Voltage Circuit-breakers, Short-Circuit Calculations, Transient Recovery Voltage.**

I. Introduction

THE evaluation of pre-existing medium voltage circuit-breakers is performed in an industrial system expansion and design stages for the connection of new loads, transformers and self-generation increase. The installation of synchronous generators, large motors, high-capacity transformers or even changes of the topology operation cause the SC current increase in the facility. High asymmetrical currents (with high X/R ratios) impose to the components (circuit-breakers and switchgears) high thermal and mechanical stresses in the fault interruption operations. Considering a large investment in pre-existing components mentioned above, it would be financially unfeasible to replace all the equipment in case of exceeding the rated capacities. For this reason, technical analysis through SC and TRV studies are carried out providing information to specify equipment in order to ensure safe operation of existing circuit-breakers. In this context, this paper aims to present instructions for medium voltage circuit-breaker supportability analysis through EMT-based programs in a real industrial system. The criteria used to model the analyzed industrial system are presented in great detail, which contributes to the reproduction of this case study in similar studies. The instructions for SC and TRV evaluation of circuit-breakers are based on the limits described by IEC standards and other references. The results are presented by discussing the effects of industrial expansion on the evaluated medium voltage circuit-breakers and the conclusions obtained from this case study. The paper is organized as follows: Sections 2 and 3 contextualize the TRV problem and the evaluation methods; Section 4 presents a suggested methodology for SC analysis of medium voltage circuit-breakers using the results obtained by ATP; Section 5 presents suggested instructions for proper industrial system modeling; The results are presented in Section 6; Section 7 presents the conclusions.

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II. Transient Recovery Voltage

Transient recovery voltage is a voltage between the poles terminals of a circuit-breaker that has high amplitude and frequency, during a fault interruption [1]. The most important characteristics for evaluating the severity of TRV are: the first voltage peak, the maximum voltage peak, and the rate of rise of recovery voltage (RRRV) [2]. The RRRV must be evaluated immediately after the fault current is interrupted. Its value must not exceed the rate of recovery of the insulating capacity of the circuit-breaker. The phenomena of "restrike" and "re-ignition" can occur if the TRV and RRRV normative limits of circuit-breakers are exceeded during the interruption process. "Re-ignition" is the resumption of the current between the contacts of the same pole of the breaker, and occurs in the interval between the zero crossing of the current and less than a quarter cycle of power frequency. After the arc extinction, the dielectric properties of the insulation mean begin to recover while the TRV increases, which may cause a new reignition of the arc. If the peak value of the TRV exceeds the limit voltage for the breakdown of the dielectric rigidity of the insulation mean, the phenomenon described as "restrike" can occur with an interval of zero current of a quarter cycle of power frequency or longer, according to [10], [11]. The time constant of the circuit and the fault type affects

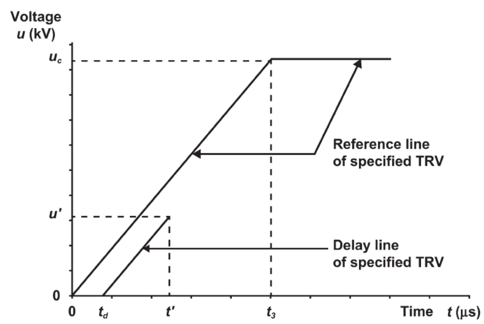

Fig. 1. Two parameters reference line [12]

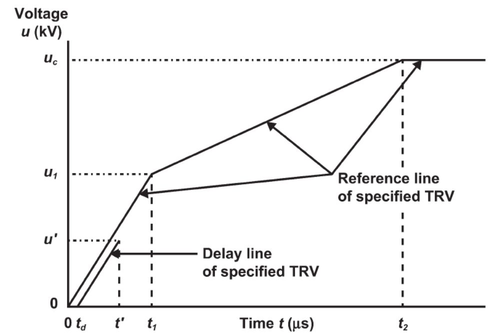

Fig. 2. Four parameters reference line [12]

the TRV severity [3]. For example, a pure inductive circuit can lead to the highest peak voltages at the terminals of the circuit breaker. Thus, the TRV values of the circuit-breakers can be changed over time, because of aging and changing of the materials characteristics used in the components of the installation, or due to significant changes in the facility, such as the connection of new loads, transformers, generators, or changes in the operation topology.

III. TRV Valuation Method

The standards IEC62271-100 [10] and IEC62271-37-013 [11] determine the rated characteristics, test procedures and technical instructions to be followed by manufacturers of circuit-breakers with voltage class above 1000 V. In [11] the applicable requirements to the generator circuit-breaker are established. From a TRV perspective, circuit-breakers are considered capable of protecting the electrical system when the TRV levels in industrial installations are below the tested limits. For circuit-breakers with a rated voltage below 100kV, or with a rated voltage above 100kV but with a terminal symmetrical SC current of up to 30% of the rated symmetrical fault current, the appropriate representation of the prospective TRV used for test duties is called a "two-parameter reference line," which is shown in Fig. 1. The voltage waveform between the terminals of the circuit-breaker must be within the envelope made by the "reference line of specified TRV" in Fig. 1. In [11] are presented the common values for the parameters of the TRV and the choice of the appropriate envelope is based on the rated power of the generator and on the type of test needed, which are: system-source, generator-source, load-current and out-of-phase. A four-parameter representation shown in Fig. 2 is applied to circuit-breakers with a rated voltage above 100kV and a terminal symmetrical fault current higher than 30% of the rated symmetrical SC current. The four-parameter representation considers the increase of the TRV voltage due to voltage wave reflections. Since the rated voltage of the circuit-breakers analyzed in this paper is less than 100kV, only the representation of the two parameters is sufficient.

IV. Short-circuit analysis of the circuit-breakers

The evaluation of the medium voltage circuit-breakers with respect to the breaking and closing capabilities under fault is done by comparing the RMS and peak SC currents obtained in the simulations performed in EMT-based programs with the rated data. Considering the time constant τ at which the circuit breaker was manufactured and the minimum interruption time t_{min} that are known, one must calculate the $Idc_{CB}\%$ using (1). This corresponds to the percentage of DC current that is permissible for the circuit breaker during an opening operation made t_{min} seconds after a short circuit. Once the percentage $Idc_{CB}\%$ is obtained, the asymmetrical SC current capability $Ib_{asym-CB}$ is calculated using (2) as suggested in [4], and compared with the RMS fault current passing through the circuit-breaker $Ib_{asym-SC}$, obtained in the simulation at the opening instant. ATPDraw has tools already implemented for obtaining the RMS value that can be used by the engineer for this purpose. The peak SC current (Ip) should be obtained graphically and compared with the circuit-breaker's rated making current, as it is related to the electrodynamic stresses caused by the closing operation during a fault. The circuit-breaker's rated peak short-circuit current should be higher than the simulated value.

$$\%Idc_{CB} = 100 * exp * (\frac{-t_{min}}{\tau}) \quad (1)$$

$$Ib_{asym-CB} = Ib_{sym-CB} * \sqrt{1 + 2 * (\%Idc_{CB}/100)^2} \quad (2)$$

The $Ib_{asym-CB}$ and Ib_{sym-CB} are given in [A], the constant t_{min} refers to the considered opening time in seconds. The variable Ib_{sym-CB} corresponds to the circuit-breaker symmetrical rated SC current, obtained from the nameplate data. To illustrate the aforementioned methodology, Fig. 3 presents a flowchart containing the described simplified short-circuit analysis.

V. System Modeling

A. Topologies and Industrial System Description

Some factors can influence the increase of the SC current, the TRV or the RRRV values in circuit-breakers of an industrial electrical system, such as the inclusion of new and significant equipment (transformers, large motors, and generators) or the alteration of the system topology. Such changes affect the equivalent impedance at the fault point, the values of the equivalent capacitances, the magnitude and asymmetry of the SC current.

Therefore, a reevaluation of the circuit-breakers is required due to the changes in topology of the industrial system

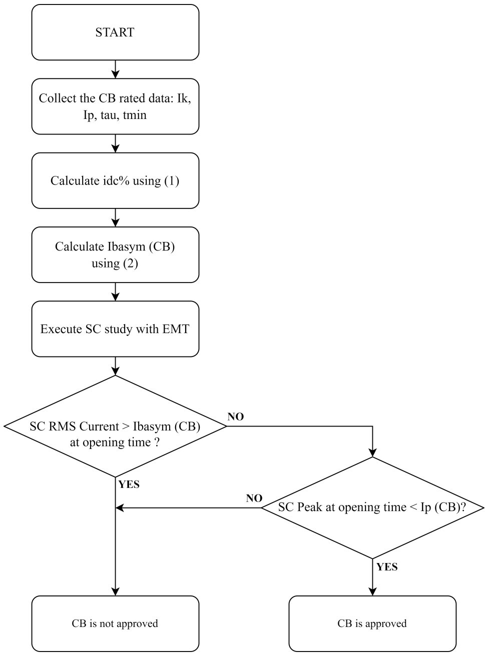

Fig. 3. Short Circuit Analysis Methodology

analyzed in this paper and described below. The power system studied is a real 107.5MW thermal power plant of own generation. The generation power is supplied by three pre-existing turbogenerators (TG1=12.5 MVA, TG2=45 MVA and TG3=50 MVA). The current topology is presented in Fig. 4, where the main substation has one step-up transformer. In the new studied topology, shown in Fig. 5, two 40/50MVA transformers are installed to increase the substation's dispatch capacity. The system operates with three turbogenerators simultaneously in both topologies. Thus, a check of the TRV and SC levels at the medium voltage circuit-breakers is required. Fig. 4 and Fig. 5 also show the locations of the faults applied in the system. Isolated and grounded three-phase faults were applied in the points showed in order to investigate the effects of SC. Although not all low-voltage motor control centers are represented in the diagrams, there are 14 MCCs in the power plant with the same topology as indicated for "LV-MCC".

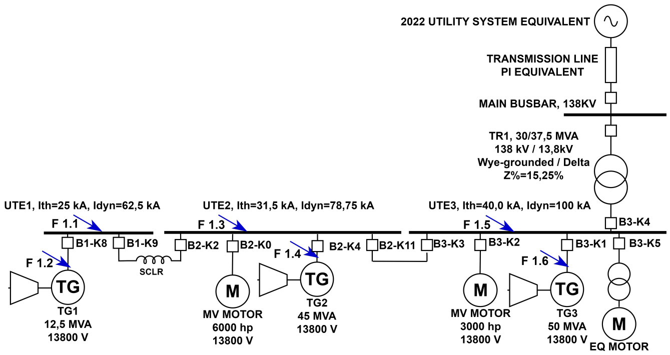

Fig. 4. Topology in 2022

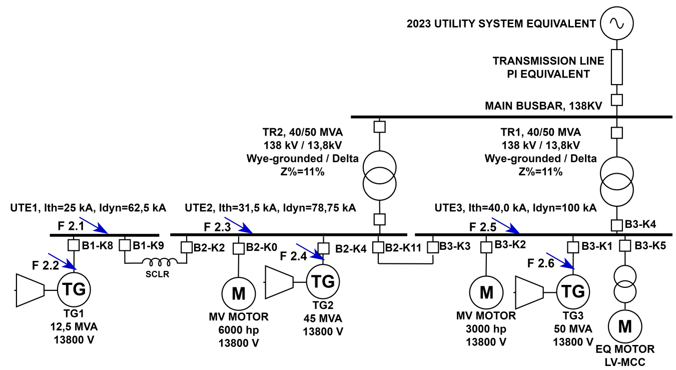

Fig. 5. Topology in 2023

B. Component Data

1) Thévenin equivalent of the power utility: The Thévenin equivalent at the point of common coupling (PCC) is modeled by a three-phase voltage source (Type 14) in series with a LINERL3S component in ATPDraw. This impedance is composed by the positive (Z1) and zero (Z0) sequence impedances using (3) and (4), considering the short-circuit current informed in the Table I, supplied by the power distribution company for the years 2022 and 2023. The nominal voltage and frequency considered are 138 kV and 60 Hz, respectively.

$$Z_{\Omega}^{1} = \frac{V_{ph-ph}}{I_{sc3Ph} * \sqrt{3}} \tag{3}$$

$$Z_{\Omega}^{0} = \frac{V_{ph-ph} * \sqrt{3}}{I_{scSLG}} - 2 * Z_{\Omega}^{1} \tag{4}$$

The V_{ph-ph} is the system line voltage, I_{sc3Ph} and I_{scSLG} are the three-phase and phase-to-ground short-circuit currents, respectively.

TABLE I
PCC SHORT-CIRCUIT DATA CONSIDERED

Short-Circuit Data per Year	2022	2023
Isc3ph (A)	20130	20970
IscSLG (A)	17870	18450
X/R seq+	8,40	8,16
X/R seq0	11,89	11,44

2) Transmission Line: The transmission line is modeled by an equivalent PI model. The information used for modeling is presented in the Table II

TABLE II
TRANSMISSION LINE DATA

Lseq+ (mH)	27.09
Lseq0 (mH)	86.28
Rseq+ (Ω)	4.15
Rseq0 (Ω)	9.24
Cseq+ (μF)	0.17128
Cseq0 (μF)	0.10536

3) Surge Arresters: Surge arresters in installations must operate as an open circuit, conducting little or no current at normal operating voltages. However, they should conduct current during overvoltages caused by lightning strikes or switching transients [5]. Although in literature detailed frequency-dependent models are related, a nonlinear resistor with an appropriate V-I curve is sufficient to represent surge arresters in switching transient studies according to [5] and [6]. Therefore, in this study the surge arresters are modeled by MOVN-Type 92 in ATPDraw. The medium voltage surge arresters used in the study are identical Hitachi MWD Station Low Class 2 and are all metal oxide (MO), non-sparking arresters. The appropriate nonlinear time response characteristic should be used, in this case the 30/60μs (MV arrester) for the switching transient studies. Table III shows the electrical data of the surge arresters to be studied in the industrial system.

TABLE III
DATA SHEET - SURGE ARRESTER MWD

Base voltage [KVrms]		
15		
Continuous Operating voltage [Uc]		
12		
Switching current impulse wave [30/60 μs]		
125A	250A	500A
kVpeak	kVpeak	kVpeak
27.4	28.5	29.6

4) Transformers: Transformers can be modeled using the saturable model for ATPDraw. The winding resistance was calculated through typical X/R ratio, estimated according to [13]. Equation (5), (6) and (7) were used to obtain the resistance and reactance of the primary and secondary windings, considering the factors α=0.5 and β=1 or β=3 for windings with wye or delta connections, respectively. When bushing and winding capacitance data are not available, the typical value of 160 pF was considered in the modeling, as suggested in [8], with the exception of the high-voltage step-up transformers used in this case study, which had their data obtained from test reports (260 pF for bushing capacitances and 87 pF for inter-winding capacitances).

$$Z_{wdg} = \alpha * \frac{Z\%}{100} * \frac{kV_{wdg}^2}{MVA} \tag{5}$$

$$R_{wdg} = \beta * Z_{wdg} * cos(atan(\frac{X}{R})) \tag{6}$$

$$L_{wdg} = \frac{\beta * Z_{wdg} * sin(atan(\frac{X}{R}))}{2\pi f} \tag{7}$$

5) Medium-voltage cables: The medium voltage cables were modeled by the LINEP3S component in ATPDraw, using the PI equivalent with concentrated parameters [9]. This representation does not impair the modeling when the distances involved are small. For longer distances it is recommended that the *Line Constants* routine to be applied to the modeling of medium voltage cables, using the cable construction data.

6) Generators: Due to the large frequency range involved in the short-circuit and in the transient recovery voltage analyses, the synchronous machines were represented by the SM59 model available in ATPDraw. The parameter data used for this representation are available in Table IV and were based on the data sheet and test reports of the power generators. The synchronous generators on the grid have a wye-grounded connection and they are grounded via a neutral grounding resistor (NGR), the only exception is the TG1 generator that operates in wye-isolated. For this reason a high grounding impedance was adopted for the TG1 generator (100 pu) in the ATPDraw. The voltage angle used by the synchronous machine model in the steady state condition was 30ř, due the phase shifts imposed by the transformers installed between the system sources.

TABLE IV
SYNCHRONOUS GENERATORS PARAMETERS

Synchronous Generators Parameters - SM59 Model			
Equipment	TG1	TG2	TG3
Frequency (Hz)	60	60	60
Power (MVA)	12,5	45	50
Voltage L-L	13,8	13,8	13,8
Poles	4	4	4
Ra	0.0047	0.0025	0.0038
Xd	2.29	1.87	1.84
Xq	2.26	1.84	1.81
Xl	0.142	0.076	0.048
Xd'	0.32	0.35	0.27
Xq'	0.324	0.42	0.35
Xd"	0.21	0.28	0.22
Xq"	0.25	0.41	0.32
Tdo'	2.3362	3.4894	3.7219
Tqo'	1.167	1.7462	1.8585
Tdo"	0.024	0.0468	0.0483
Tqo"	0.182	0.2004	0.2485
X0	0.07	0.08	0.06

7) Motors: Low-voltage induction motors with rated power greater than 40 hp were represented by equivalent motor. For these cases typical manufacturer data was used. However, the larger medium voltage motors, were modeled individually using the estimated parameters. The motors were modeled using the "Universal induction machine with manufacturer data input" (UMIND) component available in ATPDraw. To obtain the pre-fault condition, the electromechanical load equivalents were added to the "torque" terminal of the UMIND model, calculated using (8) and (9) for assigning an estimated load factor of 60% to the motors, which is a good approximation for industrial systems.

$$R_{LT} = \frac{\omega_n * 2 * \pi}{T_m * load_{pu} * freq} \tag{8}$$

$$C_{LI} = 0,04 * (hp_m * load_{pu})^{0.9} + (PP)^{2.5} * 10^6 \tag{9}$$

The C_{LI} is the equivalent capacitance relative to the load inertia given in μF, hp_m is the motor nominal power in hoursepower; PP is the number of pole pairs; $load_{pu}$ is the load in per-unit considered (60%); T_m is the motor nominal torque and ω_n is the motor rated speed in rpm.

8) Medium Voltage Circuit Breakers: The simplified representation of the circuit breakers by a three-phase ideal switch was adopted. This representation does not take into account the effect of the system on the internal electric arc that occurs in the breaker poles during the interruption process [7], however, it is a representation for the simple comparison of the inter-pole voltage levels (TRV) with the limits established by manufacturing standards. In addition to the evaluation of TRV and RRRV, this paper also aims at identifying possible short circuit current violations in the medium voltage circuit breakers, through the simplified evaluation method described in item IV. The standardized breaker opening time for this case study was 3 cycles at 60Hz. This paper considers that all the circuit breakers are the same in each medium voltage panel analyzed, with the exception of the UTE3 switchgear, which has two types of circuit breakers. Using (1) and (2) the asymmetrical short circuit capacities of the circuit breakers can be obtained, as shown in Table V.

TABLE V
MEDIUM VOLTAGE CIRCUIT BREAKERS DATA

Circuit Breakers Data				
Circuit-Breaker:	B1-K8	B2-K4	B3-K2	B3-K1
Standard:	IEC62271-100			IEC62271-37-013
Voltage(Ur):	17.5	17.5	17.5	15
Freq. (Hz):	50/60			
Current(A)	630	1250/2500	1250	2500
Ik (kA):	25	31.5	40	40
Ip:	62.5	80	100	100
τ	45ms	45ms	45ms	133ms
Ibasym	27.57	34.74	44.12	55.75

9) Short-Circuit Limiting Reactor: The short circuit limiting reactor installed between the "UTE1" and "UTE2" power houses was modeled using its nameplate data, which is described in Table VI. In addition, 75 pF capacitances were also added to each terminal of the reactor as suggested in [8].

TABLE VI
SHORT-CIRCUIT LIMITING REACTOR DATA

Rated Indutance (mH)	3.55
Losses (kW)	9.6
Rated Impedance (Ohms)	1,338
Rated Reactive Power (kVAr)	531
Nominal Current (A)	630

10) Parasitic capacitances: The parasitic capacitances were modeled according to the typical parameters suggested in [12] and [8] and presented in Table VII. The capacitances of the medium voltage busbars were also defined according to the type of compartmentalization of the cubicles. The panel described as UTE1 has an isolated (non-segregated) busbar. The other panels (UTE2 and UTE3) have a busbar compartmentalization by cubicles (segregated type). Capacitances connected between phase and ground were used to represent the current transformers (CTs), inductive potential transformers (PTs) in the wye-grounded connection, circuit-breakers and surge arresters. Potential transformers connected in delta were represented by capacitances between phases.

TABLE VII
PARASITIC CAPACITANCES

Isolated busbar (pF/m)	29,19
Segregated busbar (pF/m)	32.80
CTs (pF/unit)	180
Phase-to-ground PTs (pF/unit)	260
Phase-to-phase PTs (pF/unit)	260
Circuit-breakers (pF/unit)	300
Surge arresters (pF/unit)	80

VI. SIMULATION AND DISCUSSION

Short-circuits (both three-phase isolated and grounded) were simulated at six points of the analyzed system, chosen mainly for the analysis of the synchronous machine circuit-breakers. The analyses were carried out in two steps. In the first step, after application of the fault, each short-circuit was maintained for 30 cycles (500ms) in order to obtain the fault in steady state condition to define the appropriated envelope (T100, T60, T30, T10), for circuit-breakers manufactured according to [10]. In the second step, the same short-circuits were simulated for 3 cycles until complete extinction of the fault by opening the circuit breaker and zero crossing of the currents at the poles. In this step, the peak value of the TRV and the RRRV were evaluated and compared to the limits defined in [10] and [11], depending on the manufacturing standard of the circuit breakers. The RRRV was calculated by the maximum raise rate, expressed as the tangent line to the TRV curve passing through the origin, that is, the instant of opening of the breaker pole. The simulations of the SC currents were performed considering the system sources with initial nominal voltage of 1.1 pu, for a conservative analysis. The faults applied to the medium voltage 13.8 kV busbars (F1.1, F1.3, F1.5, F2.1, F2.3, F2.5) also were intended to evaluate the breaking and making capacity of the feeders circuit-breakers, as well as to obtain the total SC level in the medium voltage panels. The information of the SC level of the busbars is relevant for the evaluation of the thermal (Ith) and dynamic (Idyn) capacities of the busbars. The faults applied to the output terminals of the turbogenerators circuit breakers (F1.2, F1.4, F1.6, F2.2, F2.4, F2.6) were used for the compliance analysis of the synchronous machine circuit-breakers. Table VIII and Table IX show the short-circuit currents in the circuit-breakers in each simulated fault, under the 2022 and 2023 scenarios, respectively. The definition of the envelope applicable to the B3-K1 breaker is done using the definitions of [11], for this reason the envelope defined for this breaker has been set as "SS - System Source" and "GS - Generator Source". Details of the acceptable TRV and RRRV limits in each case and the highest results obtained among the three phases are presented in Tables XI and XII.

The results obtained in 2022 show no violations of the SC and TRV capacities of the circuit-breakers and panels evaluated. However, with the expansion of the substation, there are violations of the dynamic SC capacities of the

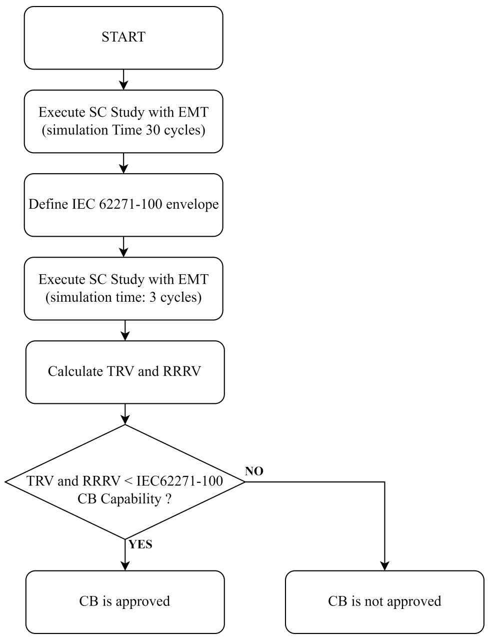

Fig. 6. TRV and RRRV Analysis Methodology acoording to IEC62271-100

circuit-breakers and the medium voltage panel UTE2, as well as overcoming the asymmetric breaking capacities of the

TABLE VIII
SC CURRENT FLOW IN THE CIRCUIT-BREAKERS ON SIMULATED FAULTS - TOPOLOGY 2022

Topology 2022 - Short Circuit Results and Envelope Defined					
Breaker - Fault Type		Ip [kA]	Ib3c[kA]	Ik [kA]	Env.
B1-K8	F1.1 3ph	7.30	2.96	0.86	T10
B1-K8	F1.1 3phT	7.30	2.96	0.86	T10
B1-K8	F1.2 3ph	18.21	7.71	4.71	T30
B1-K8	F1.2 3phT	18.21	7.71	4.71	T30
B2-K4	F1.3 3ph	20.20	9.18	3.92	T30
B2-K4	F1.3 3phT	20.20	9.18	3.92	T30
B2-K4	F1.4 3ph	58.80	23.48	11.37	T60
B2-K4	F1.4 3phT	58.80	23.48	11.37	T60
B3-K1	F1.5 3ph	27.90	12.38	4.53	GS
B3-K1	F1.5 3phT	27.90	12.38	4.53	GS
B3-K1	F1.6 3ph	50.50	20.31	11.11	SS
B3-K1	F1.6 3phT	50.50	20.31	11.11	SS

TABLE IX
SC CURRENT FLOW IN THE CIRCUIT-BREAKERS ON SIMULATED FAULTS - TOPOLOGY 2023

Topology 2023 - Short Circuit Results and Envelope Defined					
Breaker - Fault Type		Ip [kA]	Ib3c[kA]	Ik [kA]	Env.
B1-K8	F2.1 3ph	6.60	2.70	0.78	T10
B1-K8	F2.1 3phT	6.60	2.70	0.78	T10
B1-K8	F2.2 3ph	17.42	7.46	5.00	T30
B1-K8	F2.2 3phT	17.42	7.46	5.00	T30
B2-K4	F2.3 3ph	18.50	8.39	3.60	T30
B2-K4	F2.3 3phT	18.50	8.39	3.60	T30
B2-K4	F2.4 3ph	**83.50**	**35.03**	25.97	T100
B2-K4	F2.4 3phT	**83.95**	**35.03**	25.97	T100
B3-K1	F2.5 3ph	25.50	11.32	4.18	GS
B3-K1	F2.5 3phT	25.50	11.32	4.18	GS
B3-K1	F2.6 3ph	76.80	32.21	25.69	SS
B3-K1	F2.6 3phT	76.80	32.21	25.69	SS

TABLE X
SHORT CIRCUIT CURRENTS IN THE MV BUSBAR - TOPOLOGY 2022/2023

Topology 2022				
Bus - Fault Type		Ip [kA]	Ib3c[kA]	Ik [kA]
Bus UTE1	3ph	25.50	10.65	3.94
Bus UTE2	3ph	78.70	32.48	14.93
Bus UTE3	3ph	78.60	32.54	14.99
Topology 2023				
Bus - Fault Type		Ip [kA]	Ib3c[kA]	Ik [kA]
Bus UTE1	3ph	26.80	10.13	5.13
Bus UTE2	3ph	**101.00**	**42.47**	28.98
Bus UTE3	3ph	**102.00**	**42.47**	29.02

TABLE XI
TOPOLOGY 1 - 2022 - TRV RESULTS

TRV Results					
Breaker - Fault Point		TRV		Breaker Capability	
		Crest [kV]	RRRV (kV/μs)	E [kV]	RRRV (kV/μs)
B1-K8	F1.1 3ph	23.80	0.115	36.40	2.26
B1-K8	F1.1 3phT	25.35	0.118	36.40	2.26
B1-K8	F1.2 3ph	21.42	0.245	34.30	2.13
B1-K8	F1.2 3phT	19.89	0.212	34.30	2.13
B2-K4	F1.3 3ph	28.14	0.153	34.30	2.13
B2-K4	F1.3 3phT	28.03	0.140	34.30	2.13
B2-K4	F1.4 3ph	23.71	0.220	30,00	0.410
B2-K4	F1.4 3phT	20.60	0.178	30.00	0.410
B3-K1	F1.5 3ph	26.46	0.205	27.6	1.495
B3-K1	F1.5 3phT	25.00	0.188	27.6	1.495
B3-K1	F1.6 3ph	22.68	0.199	27.6	3.172
B3-K1	F1.6 3phT	19.78	0.160	27.6	3.172

UTE2 circuit-breakers. These conditions make it impossible to operate the TG3 and TG2 generating units in parallel without any measure to control the short-circuit level. These facts justify the application of solutions to reduce the level of short-circuit current in the installation, such as short-circuit limiting reactors, pyrotechnic short-circuit limiters, and the application of Back-to-Back electronic power converters. Figure 7 presents a comparison between the highest TRV values identified among the three phases for the breaker B3-K1 in 2022 (in phase A in red) and in 2023 (in phase C in green). The same analysis is presented for the circuit-breaker B2-K4

TABLE XII
TOPOLOGY 2 - 2023 - TRV RESULTS

Topology 2023 - TRV Results					
Breaker - Fault Point		TRV		Breaker Capability	
		Crest [kV]	RRRV (kV/μs)	E [kV]	RRRV (kV/μs)
B1-K8	F2.1 3ph	22.24	0.104	36.40	2.26
B1-K8	F2.1 3phT	24.30	0.107	36.40	2.26
B1-K8	F2.2 3ph	21.32	0.250	34.30	2.13
B1-K8	F2.2 3phT	18.53	0.216	34.30	2.13
B2-K4	F2.3 3ph	26.32	0.139	34.30	2.13
B2-K4	F2.3 3phT	26.32	0.129	34.30	2.13
B2-K4	F2.4 3ph	25.86	0.243	30.00	0.410
B2-K4	F2.4 3phT	23.59	0.201	30.00	0.410
B3-K1	F2.5 3ph	24.65	0.187	27.60	1.495
B3-K1	F2.5 3phT	23.56	0.173	27.60	1.495
B3-K1	F2.6 3ph	26.11	0.231	27.60	3.170
B3-K1	F2.6 3phT	23.61	0.192	27.60	3.170

in Figure 8. Based on the results, it is concluded that due to the increase in fault asymmetry in 2023, the highest TRV values occurred in different phases, and although an increase of +10% in TRV for the circuit-breaker B2-K4 and +15% for the B3-K1 was observed in 2023 in relation to 2022, there was no violation of the normative limits of TRV and RRRV of the evaluated circuit-breakers in the 2023 topology. Figure 9 exemplifies the tangent line to the TRV (in blue) used to evaluate the RRRV, after the zero-crossing of the current.

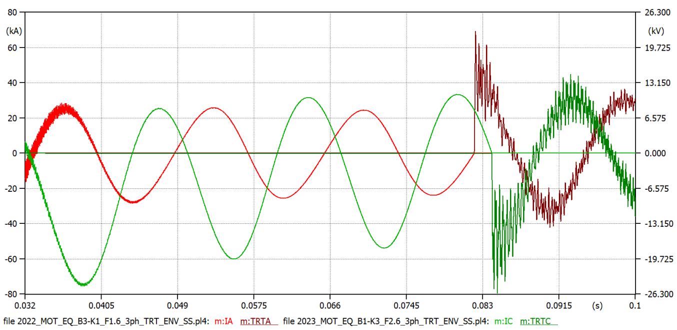

Fig. 7. Graphical TRV verified - B3-K1

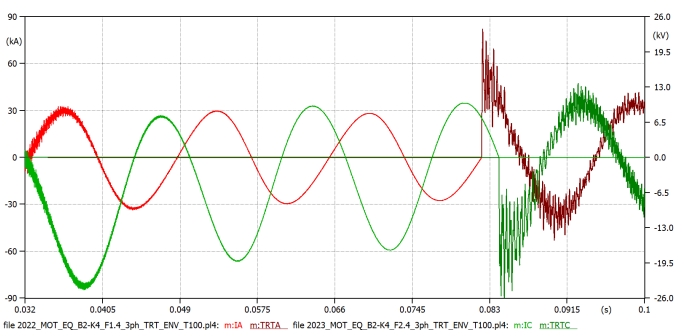

Fig. 8. Graphical TRV verified - B2-K4

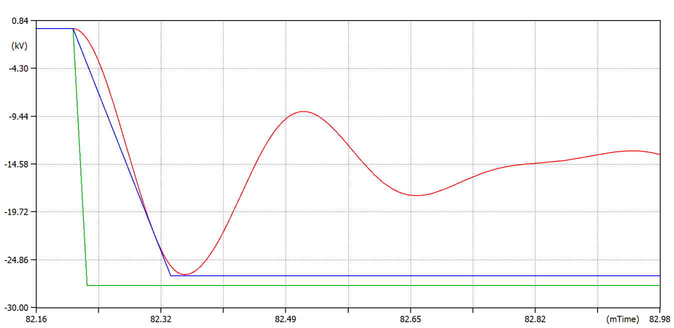

Fig. 9. Graphic representation of RRRV and maximum TRV obtained value

VII. Conclusions

This article presented a case study containing guidelines for the modeling and analysis of the TRV and SC currents of circuit-breakers and medium voltage panels in a real industrial system undergoing expansion in its high voltage substation. The modeling of the components used in the industrial system is presented in great detail, using real and typical data, which contributes to the understanding and reproduction of the methodology used in similar studies by the synthesis made in this work. In the case study, two operational scenarios (2022 and 2023) were evaluated. It was concluded that in the 2023 operational topology, the analyzed system presents higher SC levels than the dynamic capacity of panel UTE2, as well as insufficient asymmetrical interruption capacity in the medium voltage circuit-breakers of the same panel, making it impossible for the generating units to operate in parallel without the installation of equipment to control the SC level. On the other hand, based on the results of TRV and RRRV, it was found that, even with an increase in the SC power of the medium voltage installation and the asymmetry imposed by the new transformers, the topological change in the electrical system will not pose a risk of violating the dielectric capacities of the circuit breakers. As possible solutions to control the SC level of the installations, the authors suggest the installation of short-circuit limiting reactors, pyrotechnic short-circuit limiters, and Back-to-Back electronic power converters, to be evaluated in future publications.

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IX. References

[1] O. Naef, C. P. Zimmerman and J. E. Beehler, "Proposed Transient Recovery Voltage Ratings for Power Circuit Breakers," IEEE Trans. on Power Apparatus and Systems, vol. 84, no. 7, pp. 580-608, July 1965.

[2] D. G. Pimenta, J. Amon Filho, "Configuration of Subroutine MODELS of ATPDraw in Transient Recovery Voltage (TRV) Studies for Circuit Breakers," International Conference on Power Systems Transients (IPST'05), no. IPST05-205, June 2005.

[3] C. L. Wagner, H. M. Smith, "Analysis of transient recovery voltage (TRV) rating concepts", IEEE Transaction on Power Apparatus and Systems," vol. PAS-103, no. 11, 1984.

[4] R. E. Cossé, Jr., T. G. Hazel, G. Thomasset, "IEC Medium-Voltage Circuit-Breaker Interrupting Ratings-Unstated Short-Circuit Considerations," vol. no. 3, May/June 2000.

[5] J. A. Martinez, D. W. Durbak, "Parameter Determination for Modeling Systems Transients - Part V: Surge Arresters," IEEE Trans. on Power Delivery, vol. 20, no. 3, 2005.

[6] S. Abdulwadood, "Design of Lightning Arresters for Electrical Power Systems Protection," Advances in Electrical and Electronic Engineering, vol. 11, no. 6, 2013.

[7] J. A. Martinez, J. Mahseredjian, B. Khodabakhchian, "Parameter determination for modeling system transients-Part VI: Circuit breakers" IEEE Trans. on Power Delivery, vol. 20, no. 3, 2005.

[8] A. Greenwood, Electrical Transients in Power Systems, Ed. Wiley, London, 1991.

[9] CIGRE WG 33.02, Guidelines for representation of network elements when calculating transients, Cigré, 1990.

[10] High-voltage switchgear and controlgear - Part 100: Alternating-current circuit-breakers, IEC 62271.100-2021, July 2021.

[11] High-voltage switchgear and controlgear - Part 37-013: Alternating current generator circuit-breakers, IEC/IEEE 62271.37.013-2021, Oct. 2021.

[12] IEEE Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers with Rated Maximum Voltage above 1000 V, IEEE Standard C37.011-2019, May 2019.

[13] IEEE Application Guide for AC High-Voltage Circuit Breakers > 1000 Vac Rated on a Symmetrical Current Basis, IEEE Std C37.010-2016, April 2017.