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Statistical Methodology for TRV Analysis for M-SSSC Solutions in the Santa Marta Substation (Colombia)

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Abstract *– This paper presents the methodology used to evaluate Transient Recovery Voltage (TRV) of the breakers of two transmission lines considering the presence of M-SSSC devices. The study uses a statistical representation of the breakers operation in a power system grid model developed in an EMT software. The simulations performed consist in the combination of faults of different natures with different fault resistances and locations throughout the length of the line, and different points of occurrence within the voltage waveform; Analysis of all cases is based on validating if the TRV of the breakers surpasses the characteristic withstand envelopes of the breaker. The results of these tests showed that the effect of the rapid bypass protection system of the M-SSSC and the nature itself of the device (not an energy-storing element) minimize the risk of TRV violations in a power system. Finally, the same nature of tests was performed with a fixed series compensation element to compare the negative effects in TRV of fixed compensation versus the action of the M-SSSC.*

Keywords: FACTS, Series compensation, EMT simulation, TRV, RRRV, symmetric faults, asymmetric faults, M-SSSC, Power Flow Control,

1 INTRODUCTION

Modular Static Synchronous Series Compensators (M-SSSC) [1] have been globally used to actively control power flows in the existing grid by pushing power off congested lines and/or pulling power towards underutilized transmission corridors [2]. This effect is achieved by injecting a series voltage in quadrature to the line current (90° leading or lagging), thereby changing the net impedance on meshed networks and effectively optimizing grid utilization.

The implementation of these devices to improve the use of the transmission network in a safe and reliable way is increasingly common and requires studies that verify the capacity of the neighboring switches to withstand the transient recovery voltage (TRV) and its rate of rise (RRRV) against fault clearance. Every time that there are increments in the short-circuit levels in the network due to faults, the current that the breakers must clear increases, thereby increasing the required value of TRV.

It could be inferred that if the breaking capacity of a circuit breaker is greater than the maximum expected short-circuit value, the breaker would perform an effective fault clearance. However, this hypothesis is not correct, since additional requirements must be met, one of them being that the breaker must be able to withstand the TRV and RRRV produced between its poles when clearing a fault. If this is not achieved, there is a high possibility that the arc flash will reactivate, and the fault clearance operation of the breaker will not be effective.

This work presents a statistical methodology to evaluate the TRV considering the presence of M-SSSC in two circuits of the GCM operating area of the Colombian grid, where two M-SSSC deployments are to be installed in a project aimed to solve thermal overloads in the Santa Marta – Termocol 220 kV and Santa Marta – Guajira 220 kV circuits. To test if there could be any violations to TRV levels of the breaker, a comprehensive set of EMT studies was undertaken using PSCAD. A set faults with different parameter combinations are simulated in a detailed network model. The fault parameters that were modified were the nature or type of fault, time in which the fault occurs, fault impedance and the location of the fault in the line. The breaker fault-clearing

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operation corresponds to a normal distribution that randomly generates the breaker operating time around the mean. For the proposed methodology, the TRV results were compared between the M-SSSC device with respect to a legacy series reactor with the same reactance injection. A total of 2,016 simulations were carried out, where 1,008 simulations correspond to the M-SSSC and 1,008 simulations to the series reactor.

The following sections provide the context of the M-SSSC technology, its potential impact on TRV and the study methodology developed to validate said conditions. Finally, the results and comparison with the legacy solutions are presented.

2 M-SSSC SOLUTION IN THE COLOMBIAN POWER GRID

2.1 Operating Principle of M-SSSC

The assessed M-SSSC, as shown in Fig 1, injects a leading or lagging voltage in quadrature (shifted 90 degrees) with the line current, providing the functionality of a series reactor or series capacitor respectively. However, unlike conventional series capacitors or reactors, M-SSSCs can inject the voltage independently of the line current as shown in Fig 2 (left) thus controlling the effective line reactance as shown in Fig 2 (right).

Fig. 1 M-SSSC installation [2]

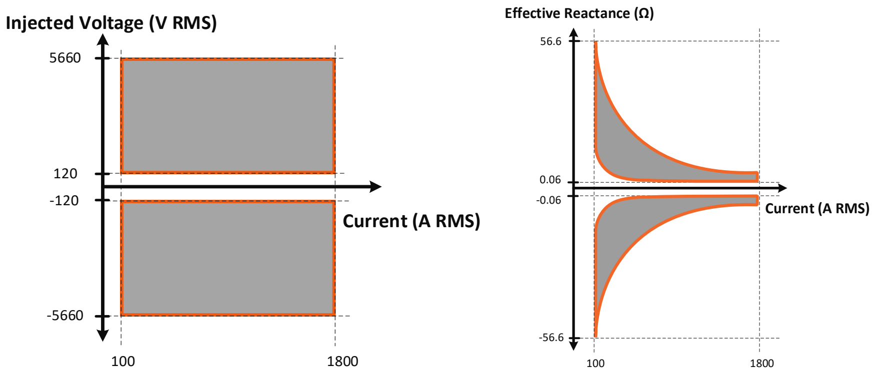


Fig. 2. M-SSSC Voltage Operating Range (left) and Reactance Operating Range (right)

An M-SSSC acts as a solid-state synchronous voltage source, consisting of a series of VSCs as shown in Fig 3. The H-Bridge of each converter uses IGBTs to inject a voltage directly into the network facility to maintain a desired reactance. This is achieved by sensing the line current through a current sensor to determine the correct voltage magnitude to inject.

Typical use cases of M-SSSC include optimizing transmission margins by releasing spare capacity in the system, alleviating thermal overloads by re-directing power flows in the existing transmission lines, and accelerating renewable interconnection by solving bottlenecks [3][4]. M-SSSC can operate in several different control modes for these use cases, including Fixed Voltage and Fixed Reactance injection. Additionally, the M-SSSC can receive dynamic set points sent remotely from integrated control centers, selected based on external signals via SCADA protocols. This flexibility in its operating principles and control capabilities offers several benefits based on the action of “dispatching” line reactance.

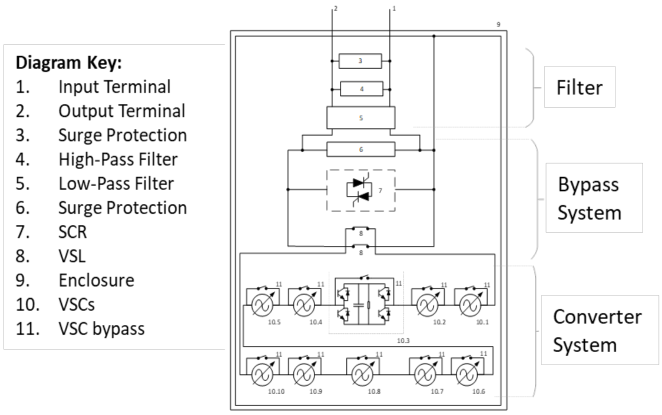


Fig. 3. M-SSSC Electrical Configuration

2.2 Primary Components of a M-SSSC

2.2.1 Filter

During system transients such as lightning surges, traveling waves can be induced into the M-SSSC. To mitigate the effects of said waves causing large voltage differentials across the M-SSSC, the filter system provides a low-impedance path for high-frequency components of line current while allowing currents around the system’s fundamental frequency to pass through the bypass and converter systems.

2.2.2 Bypass System

The bypass system provides protection and control to the converters. The principal components of the bypass are the redundant normally-closed mechanical Vacuum Switch Links (VSL), Silicon Controlled Rectifiers (SCR) and a Surge Protection. The bypass enables the rapid bypass of the converters during fault conditions and enables operators to switch the converters in series with the utility’s network facility to inject their controllable reactance for power flow control.

2.2.3 Converter System

The converter system is in charge of injecting the voltage in series with the transmission line. In the case of the M-SSSC selected for this project, it is formed by 10 converters in series, each one consisting of an H-bridge capable of injecting up to 1 MVAr at rated current.

2.3 M-SSSC at the Santa Marta 220 kV substation

The Colombian Mining and Energy Planning Unit (UPME) included an expansion project associated with the installation of M-SSSCs in the Santa Marta 220 kV [4]. UPME considered the use of said M-SSSC solutions in fixed inductive reactance mode by identifying operation scenarios in which unacceptable overloads may occur in the Guajira - Santa Marta - Termocol 220 kV ring. The reactance setpoint values were selected to ensure line current levels remain below the emergency overload limits for each circuit during N-1 conditions caused by the integration of generation plants that have been assigned firm energy supply requirements. Fig 4 (left) shows the area of influence of the solution, located in the GCM operating sub-area of the Colombian National Interconnected System (SIN in Spanish).

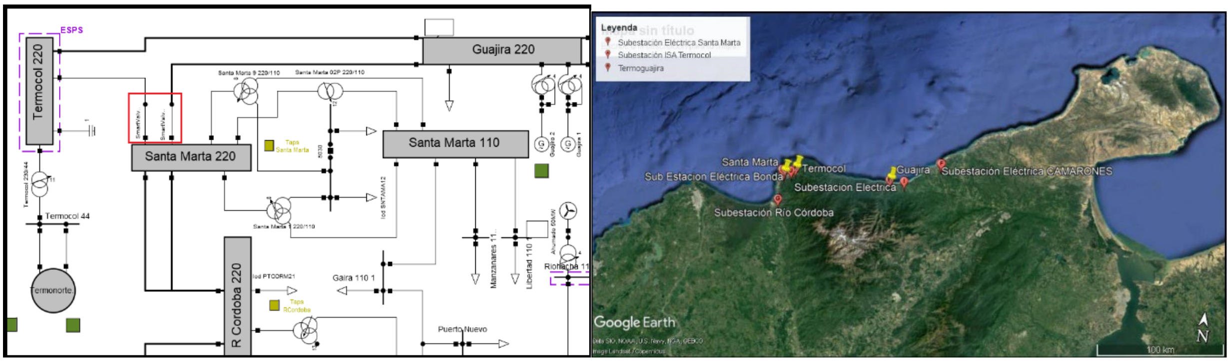


Fig. 4. Santa Marta 220 kV M-SSSC solution (left) and Geographical location of M-SSSC system (right)

The Santa Marta 220 kV and Termocol 220 kV substations are geographically located in the city of Santa Marta, and Termoguajira 220 kV is geographically located in the municipality of Dibulla in the department of La Guajira. Fig 4 (right) shows the geographical location of the solution.

3 TRV STUDY

TRV is the voltage across the opening contacts of a fault-interrupting circuit breaker immediately after the electric arc is extinguished [5]. This voltage may be considered in two successive time intervals: one during which the transient voltage exists, followed by the second one during which the power frequency voltage exists alone.

The objective of a TRV study is to verify that the TRV experienced by the circuit breaker during current interruption is within its physical capability. The nature of the TRV is dependent of the nature of the circuit being interrupted (LRC circuit behavior, travelling waves in lines). The trip signal initiates the breaker pole movement (Normal approximate time is 12 ms for contacts to get fully open), and the current is fully interrupted.

For TRV studies, the two most important factors are: the maximum voltage attained depending on the normal system operating voltage and the RRRV during oscillations, which is also dependent on the frequency of oscillations [6].

An electric arc (of very high temperature) sustains the current during the interval.

- Weakened dielectric immediately following current interruption.
- If an 'excessive' voltage is applied across the breaker immediately after the current interruption, there is a risk of re-strike.

For the TRV study considering M-SSSC at the Santa Marta 220 kV substation, a series of faults with different parameters are introduced at different length percentages of the line with the compensation devices in service. These faults will activate the modeled relays and they will send trip signal to the line breakers, which are represented using an statistical model for its opening operation. TRV will be measured at the breakers located in both ends of the line where the fault is introduced.

3.1 Considerations

3.1.1 Test System

The GCM grid model was developed in the EMT software PSCAD. The model contains all lines of the area of influence of the project using the Bergeron model and the frequency dependent (Phase) model provided natively in PSCAD. This frequency dependent model was used in the lines of interest, which are the ones of the Santa Marta – Termocol – Guarjia ring. The grid model also contains the generators, transformers, line breakers and protection distance relays that are relevant to the project. Part of the network model including the M-SSSC deployments is presented in Fig 5.

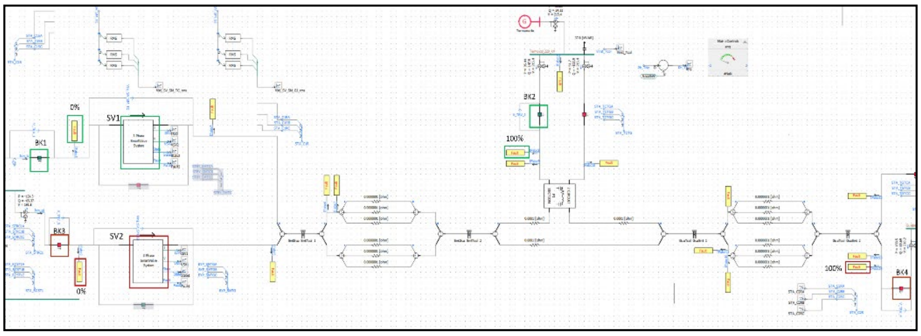


Fig. 5. GCM Network Model in PSCAD

3.1.2 TRV envelopes and breaker model

Fig. 6 shows the normal distribution curve used to simulate the statistical behavior of the circuit breaker. The Y-axis is the probability, and the X-axis is the samples generated randomly (closing time for the breaker) around the mean value [7]. The number of standard deviations considered in this study is 3, with a minimum delay of 0 sec and maximum delay of 0,006 sec.

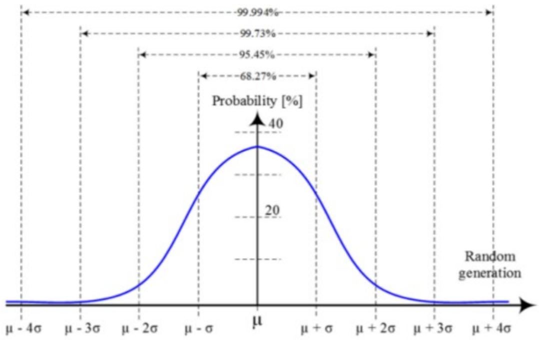


Fig. 6. Normal Statistical Generation of Sample Closing Time for Breaker – PSCAD

For the TRV envelopes, given that the M-SSSC solution is installed at 220 kV voltage level, an IEEE four-parameter envelope was used , with a TRV class of EENS (100 kV to 800 kV), and a rated voltage of 245 kV [8]. Fig. 7 shows the four parameter TRV envelop implemented in PSCAD.

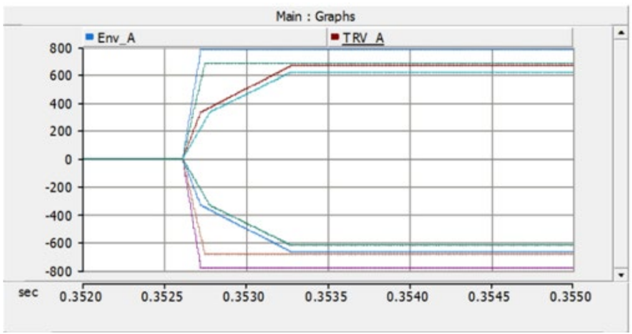


Fig. 7. Four-parameter IEEE TRV Envelope

3.1.3 Fault Parameters

The fault parameters that were combined to generate all the simulation cases are the following:

- Fault location: The faults are applied at 1%, 5%, 50% and 99% of the line's total length.
- Type of fault: Single-phase-to-ground, two-phase-to-ground, three-phase-to-ground and isolated two-phase faults are to be considered.

- Time where the fault occurs: The fault is applied at 0.01s, 0.015s and 0.02s after the system reaches steady state.
- Fault impedance values: The chosen values were the ones that did not cause the operation of internal protection of the M-SSSC devices that commands them to go into bypass mode, as the purpose of the study is to check the implications of having these devices in service when a fault occurs in the system.

3.1.4 M-SSSC operation

As mentioned in Section 2, the M-SSSC will operate in a fixed reactance mode in order to keep the current levels below the overload limit of the line in case of an N-1 contingency in the area of influence. The setpoints were previously calculated to ensure a normal loading in the lines. These values are 27Ω for the M-SSSC installed in the Santa Marta – Termocol 220 kV deployment and 17Ω for the M-SSSC installed in the Santa Marta – Guajira 220 kV. Additionally, in order to test if a capacitive voltage injection of the devices could cause any TRV violations, -27Ω and -17Ω setpoints were also considered. These values of capacitive injection imply the Santa Marta – Termocol line is overcompensated, which has other implications in the traditional operation of power systems that are not the focus of this work.

3.1.5 Series Reactor operation

One of the typical study scenarios for TRV analysis is reactor and transformer de-energization as series reactors are typically used as fault current limiters (FCLs) to avoid power grid protection issues. As a counterpart, risks of TRV in the circuit breaker increase due to FCL's high stored energy [9]. In addition to that, the TRV phenomenon depends on the equivalent inductance, impedance, and capacitance of the faulty system. Moreover, the inductance of a faulty electric system increases with the presence of superconducting fault current limiter (SFCL), as they can affect TRV parameters such as the peak of TRV, frequency, rate of raising recovery voltage (RRRV), and TRV damping constant [10].

Therefore, for this part of the study, a comparison between the M-SSSC devices and series reactor with the same inductance injected by the M-SSSC is performed. To accomplish this, the series reactor model also considers a parallel capacitance in accordance to the inductance value. The information on [11] was used to calculate the parallel capacitance in relation to the representative inductance tested on the M-SSSC device.

TABLE I. SERIES REACTOR VALUES

M-SSSC	Inductance (mH)	Capacitance (pF)
SM – TC	71.60	8.8
SM – GJ	45.10	14.0

4 TEST RESULTS

Four (4) set of cases were performed with a total of **2.016 different simulations**:

- M-SSSC – inductive injection (504 cases)
- Series reactor – Equivalent to inductive injection case (504 cases)
- M-SSSC – capacitive injection (504 cases)
- Series reactor – Equivalent to capacitive injection case (504 cases)

The following sections summarize the results of said simulations.

4.1 Santa Marta – Termocol 220 kV circuit (SM-TC)

TABLE II. SIMULATION CASES- SANTA MARTA – TERMOCOL 220 KV

1Ph-g, 2Ph-g, 3Ph-g and 2Ph isolated faults	Number of cases with M-SSSC in injection				Number of cases with fixed compensation			
	Inductive		Capacitive		Inductive case characteristics		Capacitive case characteristics	
	BK1	BK2	BK1	BK2	BK1	BK2	BK1	BK2
1% All	0	0	0	0	0	0	0	0
5% All	0	0	0	0	0	0	0	0
50% All	0	0	0	0	0	0	0	0
99% All	0	0	0	0	0	0	0	0

For the SM-TC circuit, no case exceeded the limits of the envelopes, this is due to the high fault impedance values for which the M-SSSC does not go to Bypass. Therefore, the fault current is lower and the TRV amplitude is also lower.

4.2 Santa Marta – Guajira 220 kV circuit (SM-GJ)

TABLE III.SIMULATION CASES- SANTA MARTA – GUAJIRA 220 KV, 1PH-G, 2PH-G AND 3PH-G FAULTS

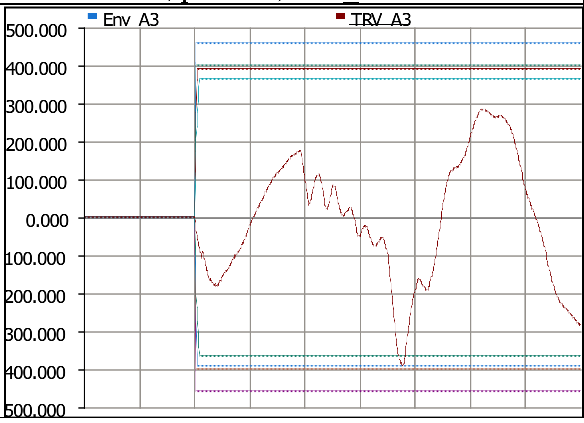
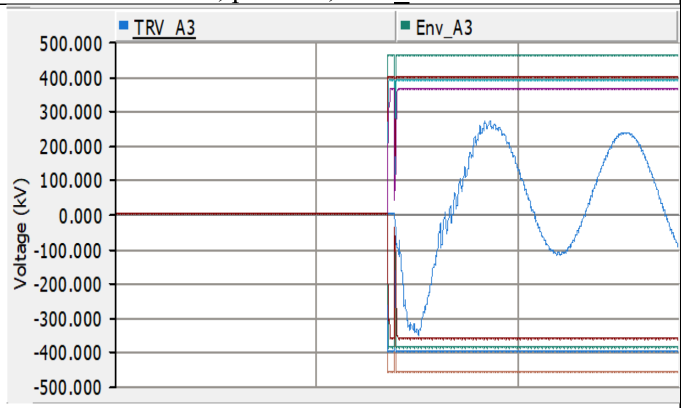
1Ph-g, 2Ph-g and 3Ph-g faults	Number of cases with M-SSSC in injection				Number of cases with fixed compensation			
	Inductive		Capacitive		Inductive case characteristics		Capacitive case characteristics	
	BK3	BK4	BK3	BK4	BK3	BK4	BK3	BK4
1% All	0	0	0	0	0	0	0	0
5% All	0	0	0	0	0	0	0	0
50% All	0	0	0	0	0	0	0	0
99% All	0	0	0	0	0	0	0	0

TABLE IV. SIMULATION CASES- SANTA MARTA – GUAJIRA 220 KV, TWO-PHASE ISOLATED FAULT

Two-phase unground fault [8]	Number of cases with M-SSSC in injection				Number of cases with fixed compensation			
	Inductive		Capacitive		Inductive case characteristics		Capacitive case characteristics	
	BK3	BK4	BK3	BK4	BK3	BK4	BK3	BK4
1% All	0	0	0	0	3	3	3	3
5% All	0	0	0	0	0	0	0	0
50% All	0	0	0	0	0	0	0	0
99% All	0	0	0	0	0	0	0	0

For the SM-GJ circuit, none of the cases that consider the M-SSSC device exceeded the limits of the envelopes, this is due to the high fault impedance values for which the M-SSSC does not go to Bypass. However, for three cases that consider the equivalent series reactor, the envelope limits are passed 6 times per simulation. This occurred on phase A for the breakers in both ends of the line. These cases correspond to a **Two-phase isolated fault**, located 1% from Santa Marta substation, with a fault impedance of 36 ohms. This is likely due to the series reactor energy storage characteristic. The graphs of these cases are shown in TABLE V.

TABLE V. TRV RESULTS FOR M-SSSC IN INDCUTIVE REACTANCE MODE VS SERIES REACTOR WITH EQUIVALENT IMPEDANCE OF M-SSSC IN INDUCTIVE MODE, TWO-PHASE ISOLATED FAULT

Series reactor (inductive) BK3, phase A, FLT_R = 36Ω	M-SSSC (inductive) BK3, phase A, FLT_R = 36Ω
	

5 CONCLUSIONS

The fault impedances required for the M-SSSC not to enter Bypass mode are relatively high and change depending on the characteristics of the network. These impedance fault values reduce the critical scenarios in which the TRV could exceed the envelopes of the IEEE C37.011™-2019 standard.

In the 1008 cases that were simulated with M-SSSC (inductive and capacitive injection), in which fault type, location, time of fault and breaker opening time were modified according to a random statistical sample, the limits of the envelopes were not exceeded in any of the cases. The series reactor on the other hand, exceeded the TRV envelope limit for an isolated two-phase fault located at 0% of the line.

The study was performed with a detailed model of real installation and following the standard methodology for legacy series compensations solutions. Results show that there is a benefit when using M-SSSC devices, as they can provide a controllable series compensation without affecting TRV in line breakers.

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