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Analysis, Design, Implementation and Validation of an RTDS test benchmark for system integration of M-SSSC solutions in the Santa Marta substation (Colombia)

A. DUQUE*	**J.A. CALDERON**	**C.E. BORDA**	**S. HINCAPIE**	**J.P. BOTERO**
Smart Wires Inc.	**ISA**	**Smart Wires Inc.**	**Smart Wires Inc.**	**Smart Wires Inc.**
Colombia	**Colombia**	**Colombia**	**Colombia**	**Colombia**
alejandro.duque[1]	jacalderon[2]	carlos.borda[1]	sebastian.hincapie[1]	juan.botero[1]
M. HAMMAD	**D. CARO**	**P. MACEDO**	**C.A. RESTREPO**	**J.P. GALLEGO**
Smart Wires Inc.	**Smart Wires Inc.**	**Smart Wires Inc.**	**ISA**	**ISA TRANSELCA**
Germany	**Colombia**	**United States**	**Colombia**	**Colombia**
mohammad.hammad1	dilan.caro[1]	pablo.macedo[1]	crestrepo[2]	jpgallego[3]

Abstract *– This paper presents the experience gained during the design and implementation of the performance tests in the Real Time Digital Simulation (RTDS) system for a real power flow control solution based on M-SSSC devices and applied to the Colombian power grid. The tests benchmark is aimed to cover functional performance, harmonic emission, background harmonic immunity and dynamic performance in real operation scenarios. The tests were instrumental to validate the proper integration of the M-SSSC installations with the existent components of the power grid, to define their settings and specify improvements to existing functionalities. Finally, this paper establishes a series of good practices identified from the experience of real transmission systems of the ISA group to incorporate them to the installation of this novel technology and promote the safe expansion of this type of solutions all over the world.*

Keywords: FACTS - Series compensation - Real time simulation- RTDS- HIL- M-SSSC- Power Flow Control - Distributed FACTS

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.

This paper describes the process of analysis, specification, design, construction, and the results of the execution of RTDS tests for two M-SSSC systems for the Santa Marta 220 kV substation in Colombia. The main objective of these two M-SSSC installations is to provide power flow limitation and avoid thermal overloads of the Santa Marta - Guajira 220 kV and Santa Marta - Termocol 220 kV circuits caused by contingencies in any of these two circuits. The definition of the methodology and detailed scope of each of the test stages was developed jointly by a multidisciplinary team of the transmitter (ISA and ISA Transelca) and the developer of the M-SSSC solution (Smart Wires), achieving not only an adequate coverage of tests that guarantee the safe integration of the M-SSSCs, but also the definition of improvements to the existing functionalities and the development of a backup function supported by the protection relays at the substation.

Three main stages were executed, functional performance tests (FPT), harmonic tests and dynamic performance tests (DPT). The description, methodologies and tools developed for their execution and the analysis of their results are presented. This work highlights the automation, the definition of variations with different locations of the M-SSSC as well as real relays, which allowed an agile and effective analysis in an environment very close to what operation engineers are used to with in real life. In the conclusions, key findings made during the acceptance process of this technology is presented, confirming it is a viable solution with great potential to respond to the modern challenges in transmission network expansion.

* Calle 7D# 43A – 40, Medellín, Colombia – [1]@smartwires.com [2]@isa.com.co [3]@transelca.com.co

2 M-SSSC SOLUTION IN THE COLOMBIAN POWER GRID

2.1 Operating principle of M-SSSC

The assessed M-SSSC shown in Fig 1 (left), injects a leading or lagging voltage shifted 90 degrees with the line current, providing the functionality of a series reactor or series capacitor respectively. However, unlike legacy solutions, 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).

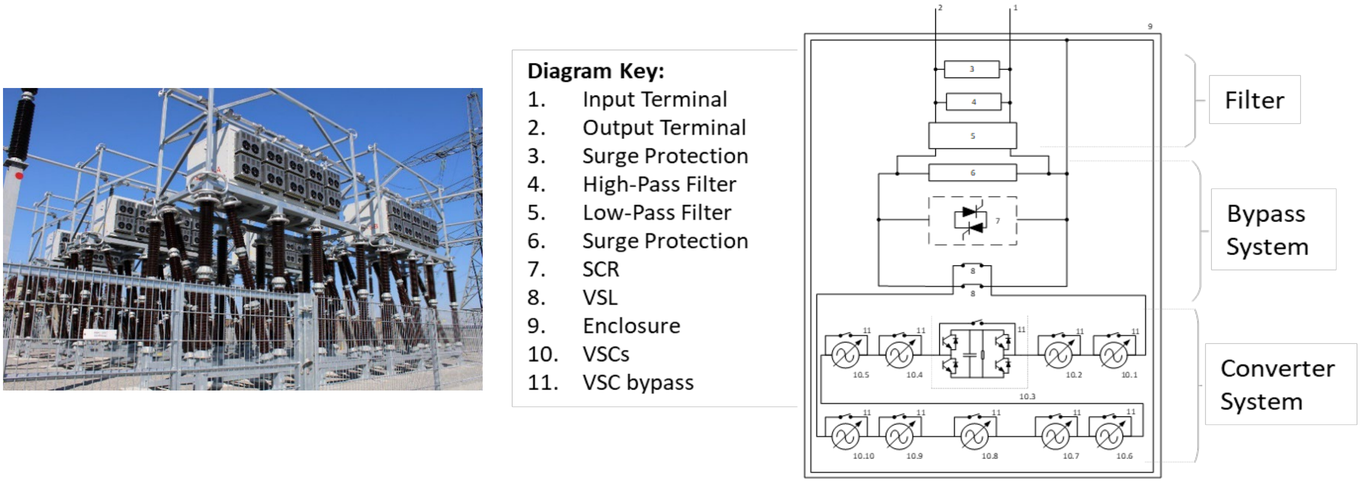

Fig 1. M-SSSC installation (left) and electrical configuration (right) [2]

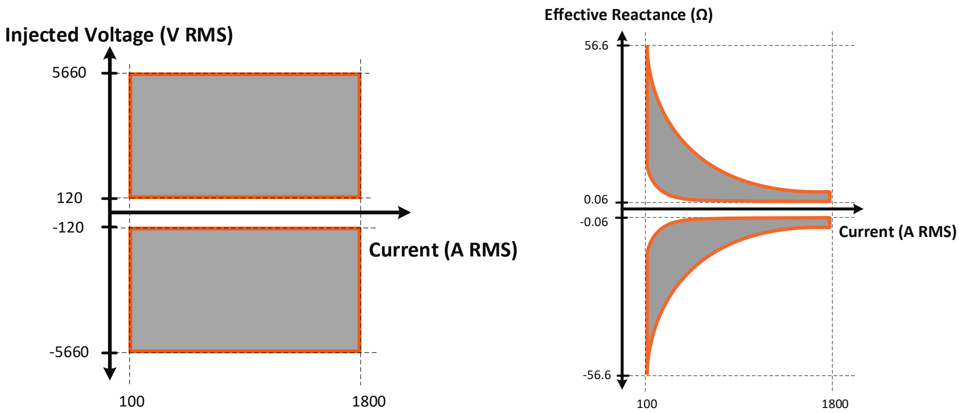

Fig 2. M-SSSC Voltage Operating Range (left) and Reactance Operating Range (right)

An M-SSSC consists of a series of VSCs as shown in Fig 1 (right). The H-Bridge of each converter uses IGBTs to inject voltage directly into the network facility to maintain a desired reactance. This is achieved by sensing the line current through a current sensor and determining the correct voltage magnitude to inject.

Typical use cases of M-SSSC include optimizing transmission margins, alleviating thermal overloads by re-directing power flows in the system, and accelerating renewable interconnection by solving bottlenecks [3][4]. M-SSSC operate in several different control modes, including Fixed Voltage and Fixed Reactance injection. Additionally, M-SSSC can take comands sent remotely from the EMS based on external signals monitored via SCADA. This flexibility offers benefits based on the action of “dispatching” line reactance.

2.2 Primary components of 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), SCRs 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. The bypass action can be performed via the VSLs (permanent bypass) or via the Low Overcurrent Ride through (LOR) feature, which consists of a temporary bypass halting VSC injection via the IGBTs when line current is over a configurable limit.

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 3 (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).

UPME proposed a M-SSSC solution based on the installation of two M-SSSC deployments as follows:

- On Santa Marta – Termocol 220 kV circuit: 15 M-SSSCs -5 per phase
- On Santa Marta – Guajira 220 kV circuit: 9 M-SSSCs -3 per phase

The solution also takes advantage of the possibility of relocating M-SSSC units. Thus, it will have a second stage with the following reconfiguration:

- Relocation of the 15 M-SSSCs on the Santa Marta - Termocol 220 kV circuit to the Termoguajira - Termocol 220 kV circuit.

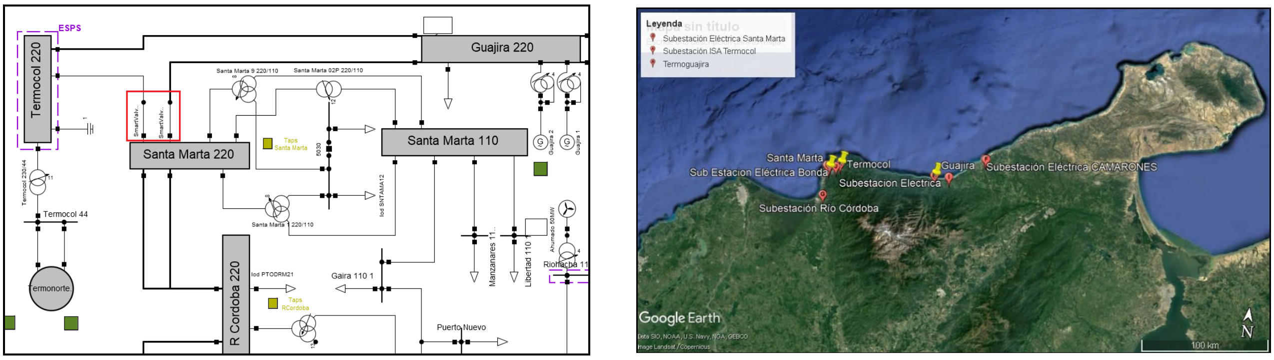

Fig 3 Santa Marta 220 kV M-SSSC solution (left) and Geographical location of M-SSSC system (right)

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 3 (right) shows the geographical location of the solution.

3 RTDS TEST SPECIFICATION

Once the behavior of the M-SSSC devices in steady state conditions has been identified and their ability to mitigate potential overloads has been verified via system integration studies, it became relevant to validate the dynamic behavior of the real controls when facing system disturbances of different characteristics that could occur in the electrical by using real-time simulations [5]. The designed benchmark analyzes three test groups in detail: Functional performance Test (FPT), Harmonic Injection Test, and Dynamic Performance Tests (DPT). The results of these tests become relevant to validate the interaction of M-SSSC with existing components such as protection schemes, among others. This validation will help operators to anticipate the behavior that the system would have before the occurrence of typical and critical events in the power grid.

3.1 Test setup

To test and verify the performance of M-SSSC system in the customer's power network, a Control Hardware in the Loop (C-HIL) test set up has been developed by utilizing Real Time Digital Simulator as shown in Fig 4. RTDS is an ideal tool for testing power electronics control devices in power systems. The purpose of the C-HIL is to avoid bugs associated with Firmware and Hardware before installing the device in the field.

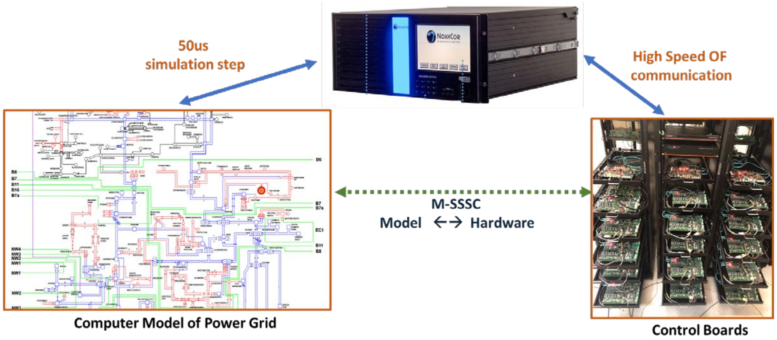

Fig 4. C-HIL overview for an M-SSSC solution

To account for several M-SSSCs connected in series, a hybrid arrangement can be implemented as seen in Fig 5. One M-SSSC is studied in C-HIL, and the remaining M-SSSCs are represented as RSCAD models in a Software-In-Loop (SIL) arrangement. The bi-directional communication between C-HIL and SIL is done via RTDS GTNET cards [6] and M-SSSC's proprietary communication equipment.

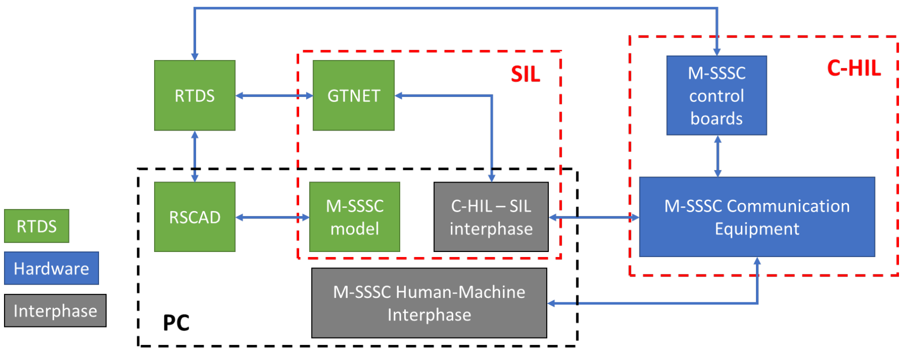

Fig 5. High-Level Schematic of hybrid C-HIL + SIL arrangement

The C-HIL set up was sufficient to run Functional Performance and Harmonics tests. Nonetheless, Dynamic Performance Tests required to validate the operation of the M-SSSC with protection relays in the loop (PIL). Fig 6 illustrates the implemented C-HIL + PIL setup used. RTDS on the right connects to the relays and amplifiers interacting with the RSCAD simulation. RTDS on the left connects to the C-HIL setup and transmits the analog signals from the ongoing simulation to the M-SSSC control boards, which return the device's digital outputs to the RSCAD simulation. Both RTDS systems are interconnected via Fiber Optics.

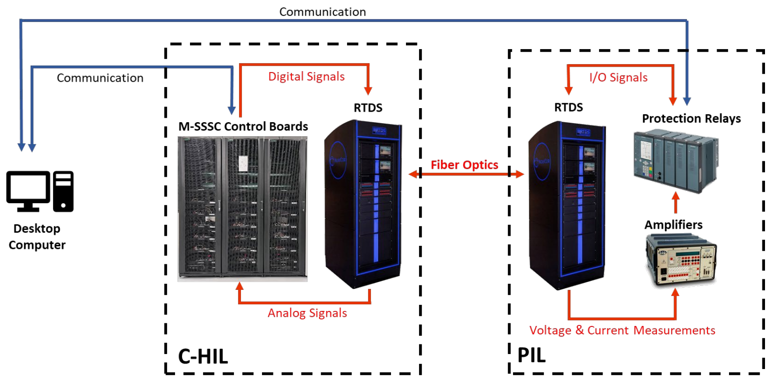

Fig 6. C-HIL + PIL setup

3.2 Functional performance test (FPT)

The FPT system uses the C-HIL set up and consists of a three-phase model composed of a controllable current source and the M-SSSC as shown in Fig 7.

- **Current Source** Each phase has its own current controller that allows to adjust the frequency, phase angle and magnitude of the line current.
- **M-SSSC** Each phase is modeled with an individual M-SSSC controller. The communication between the controllers is used to synchronize the voltage injection and fault states between network phases. The HIL modelling block contains the C-HIL interface presented in Fig 4.

FPT tests demonstrate the basic functional behavior of the M-SSSC system. These tests include operation in steady-state as well as during ramping up and down for inductive and capacitive injection. Transient conditions are considered and help demonstrate how the M-SSSC operates while it is subjected to various disturbances. Transient cases include step changes in line loading, shift in current phase, and system frequency.

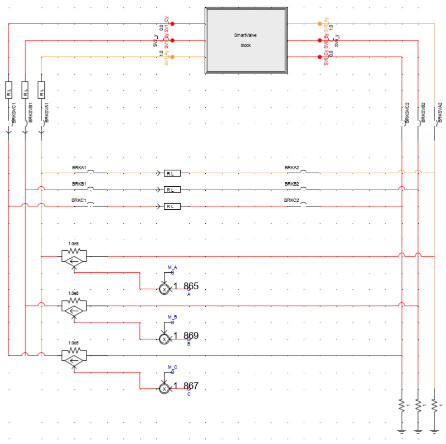

Fig 7. FPT System Single Line Diagram

3.3 Harmonic emissions & immunity test

The Harmonic tests validates M-SSSC's harmonic emissions and its response to system background harmonics. The test uses the C-HIL set up and monitors the model's behavior for a given range of harmonics measured in the real system. The intend of this test is to validate the results from a comprehensive harmonics study previously performed in PSCAD.

Fig 8 shows single-phase test system used for the harmonics test. The modelled system includes a reduced frequency dependent representation of the transmission lines within the Santa Marta - Guajira - Termocol 220 kV ring along with Foster-Cauer equivalent analogue circuits [7] of the surrounding network. To replicate the exact same background harmonic conditions measured on site and considered in the PSCAD study, a set of harmonic voltage sources were used, which inject voltages for each of the relevant harmonic orders that replicate the magnitudes measured on site.

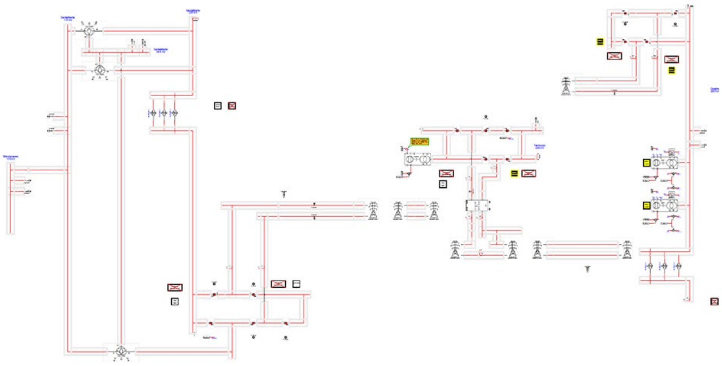

Fig 8. Harmonic Injection Test Single Line Diagram.

3.4 Dynamic performance test (DPT)

DPT uses the C-HIL + PIL set up (Fig 6) to validate M-SSSC and protection scheme response to realistic and critical system faults likely to be experienced in field [8]. The tests grouped in DPT come from subset of cases selected from a comprehensive PSCAD Dynamic Performance Study. During DPT, the system AC network is simulated in RTDS, the size of the network is constrained due to the RTDS hardware capability. The starting point for this simplified network model is the area of influence of the project shown in Fig 3. The network model is depicted in Fig 9. The network model accuracy was tested against load flow results and dynamic simulations using the National Interconnected System database available in PowerFactory. Automations and case variations with different locations of the M-SSSC equipment and the real relays were developed to allow an agile and effective execution in an environment very close to the one in which operation engineers are used to validate this type of events in their day-to-day work.

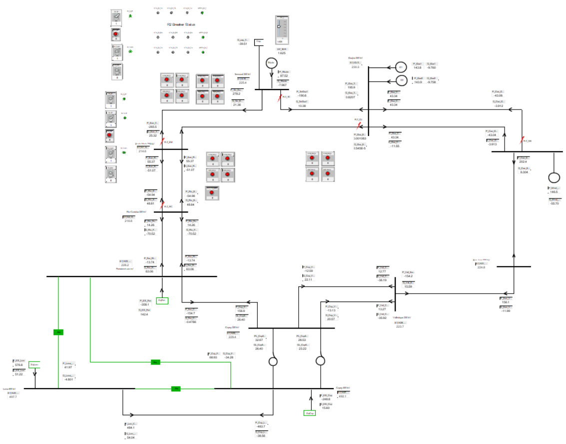

Fig 9. Dynamic Performance Test Single Line Diagram.

4 TEST RESULTS

4.1 FPT

FPT tests demonstrated the basic functional behavior of the M-SSSC in steady-state conditions and during ramping for both inductive and capacitive injection. Fig 10 illustrates one example of the M-SSSC´s LOR feature described in section 2.2.2. Transient cases in FPT flagged first firmware modifications to ensure a proper response of the M-SSSC solution to a comprehensive set of disturbances.

FPT also helped to test HMI performance while testing different commands online and exporting system records in COMTRADE format.

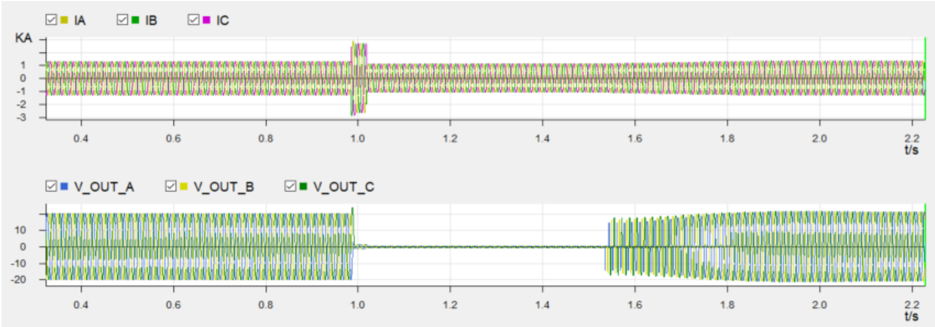

Fig 10. FPT – LOR validation

4.2 Harmonic emissions & immunity

Harmonic emission analysis for M-SSSC installations confirmed that the algorithms implemented to optimize duty cycles of the converters helped to meet the requirement that incremental magnitude occupancy for the added voltage harmonic distortion caused by the M-SSSC devices stays within the allowable limits for the project. M-SSSC injection caused a minimal increment on harmonic conditions below 0.1% for voltage and below 0.5% for current, indicating proper operation for the expected conditions on site.

Hamonic Immunity analysis showed a good performance of the M-SSSC control system facing background harmonic conditions. The M-SSSC's PLL successfully locks to the line current phasor and injects voltage in quadrature to its fundamental component for all considered cases, confirming that the M-SSSC devices won't see their operation restrained by the existing harmonic content present in the system.

4.3 DPT

DPT confirmed that if the current through the M-SSSC devices exceeds the overcurrent threshold, it causes the transition from injection to monitoring mode (bypass state). This is the expected performance, especially for those cases where the fault occurs in the same line where the M-SSSC is located. In addition, all the cases show that the M-SSSC solutions transition to monitoring mode (bypass state) in less than 5 ms.

DPT cases were instrumental in finalizing configurable settings of the M-SSSC solution. Tests captured ISA's best practices in protection coordination and were focused on ensuring a proper coordination between M-SSSC's bypass actions -either from the temporary operation of LOR or the definitive closing of VSLs- with the protection schemes of the nearby system. These results were shared with Colombia's ISO and served as validation for a mandatory protection coordination study prior to project energization.

4.4 Key findings and improvements

Given that this was the first M-SSSC project executed between ISA and Smart Wires, the successful completion of these tests required a close iterative work between both teams. Several visits to the RTDS laboratory were held to gather team's feedback and develop a testing methodology that captured Smart Wires experience deploying M-SSSC solutions globally and ISA's long experience operating FACTS in LatAm.

First major challenge was limited access to physical control boards for the C-HIL set up. Due to supply chain issues in the power electronics industry globally, the C-HIL could only represent up to three M-SSSCs. This required the team to develop solutions such as detailed M-SSSC models in RSCAD and the hybrid C-HIL+SIL arrangement shown in Fig 5. Models were validated and adjusted using the physical control boards and firmware as reference. This situation in conjunction with a limited availability of protection relays connected to the RTDS led to additional solutions where location of real and modelled M-SSSCs and relays was interchanged using predefined cases and RSCAD automations. Additionally, a case representing three real devices connected in series in one phase was created to validate algorithms during harmonic tests.

FPT cases were key to provide ISA with a first approach to the device firmware and its real operation. This was not only helpful to determine initial modifications that ensured a proper M-SSSC response to a comprehensive set of disturbances, but also served as a starting point to specify basic function diagrams following industry's best practices and giving ISA the tools to evaluate M-SSSC performance in field.

One of the major outcomes came from DPT was the operation of LOR. This operation was designed to be a single-phase feature that was backed up by the three-phase operation of the VSLs (permanent bypass). First results in PSCAD indicated potential risks due to the operation of the LOR independently on each phase. If M-SSSCs are injecting a significant amount of voltage that is diverting a considerable amount of power flow, the single-phase response of the LOR could extend unbalanced conditions after the fault is cleared. These unbalanced conditions in the healthy line may trigger the zero-sequence overcurrent protection logic of the line relays, thus, increasing the risk of N-2 contingencies. This potential risk was confirmed during DPT with a single-phase fault at 50% of the Santa Marta - Guajira 220 kV line, where single-phase LOR response of the M-SSSC caused two circuits to trip simultaneously, posing a risk of total black out in the GCM area.

These findings triggered the improvement of LOR to operate on the three phases simultaneously, leveraging on the fast fiber optics communication between devices requested by ISA for the project. Additionally, ISA designed a backup response of the M-SSSC triggered by the line protection relay right next to each M-SSSC installation. This back-up scheme aims to cover all possible scenarios that could cause an unbalanced condition in the system. This so-called *LOR backup* logic is shown in Fig 11 and consists of commanding the M-SSSC to activate the LOR response on the three phases of the M-SSSC when any of the conditions in the figure is met. This backup LOR logic is wired directly from the protection relay to the control and communication system of the M-SSSC. It will act alongside the built-in protection functions of the M-SSSC to conform a very robust system that ensures a correct behavior of the device and the protection relays of the area of influence of the project.

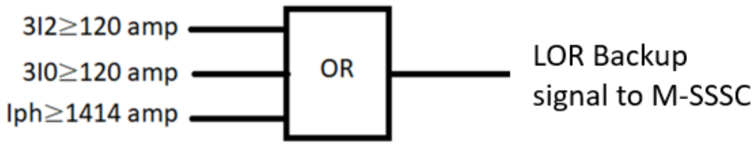

Fig 11. LOR backup logic

Firmware on the C-HIL was updated to include the three-phase operation of LOR. LOR backup logic was implemented in one of the real protection relays, and the whole solution was validated in DPT by wiring both devices directly on the C-HIL + PIL set up shown in Fig 6. The solution was successful in avoiding potential N-2 contingencies as the fault mentioned before, proving to be an effective solution.

5 CONCLUSION

This work summarizes the analysis, design, implementation, and validation of the performance test benchmarks in the RTDS for a real power flow control solution based on M-SSSC in the Colombian power grid. The tests were instrumental to ensure a proper integration of the M-SSSC solutions with the existing grid, establishing a series of good practices built from the experience of real transmission systems in the ISA group.

Relevant aspects identified and resolved during the RTDS testing process provided technical assurance to consider M-SSSC as an effective solution with great potential to achieve an optimal, sustainable network that responds to the challenges imposed by the modern paradigm in transmission network expansion.

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