20th International Conference on Renewable Energies and Power Quality (ICREPQ'22)
Vigo (Spain), 27th to 29th July 2022
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.20, September 2022

Analysis of the Impact of a Modular SSSC on the Operation of Transmission Line Protection Relays using a Hardware-In-the-Loop Configuration

B. Polajžer[1], A. Trupej[1] and P. Xenos[2]
[1] Faculty of Electrical Engineering and Computer Science, University of Maribor
Koroška cesta 46, 2000 Maribor, Slovenia
e-mail: **bostjan.polajzer@um.si**, **aljaz.trupej@student.um.si**

[2] Smart Wires Inc.
Glencullen House, Kylemore Road, Dublin 10, D10 CA33, Ireland
e-mail: **panos.xenos@smartwires.com**

Abstract. This paper evaluates the impact of a modular Static Synchronous Series Compensator (m-SSSC) on the operation of communication-assisted line distance and differential protection relays. The m-SSSC system incorporates an over-current protection feature to trigger the bypass mode of operation during grid faults. A case study is analyzed for a 220 kV transmission line and an m-SSSC with a reactive power rating of 80 MVAr per phase using a Hardware-In-the-Loop configuration. The obtained results show the impact of the m-SSSC system on the distance protection operation during some cases of high resistive faults. The differential protection operation was not affected by the m-SSSC.

Key words. FACTS, Static Synchronous Series Compensator, Hardware-In-the-Loop, Transmission Line Protection.

1. Introduction

Energy flow control plays a vital role in a secure and profitable power system operation. One of the promising and commercially available FACTS solutions is a Static Synchronous Series Compensator (SSSC) [1], [2], which is also used to enhance power system stability [3-5]. However, since an SSSC changes the effective line reactance, it should bypass during grid faults to enable reliable operation of protection relays [6]. This paper investigates the impact of a modular SSSC on the operation of the transmission line protection relays using a Hardware-In-the-Loop (HIL) configuration. Two numerical relays, Siemens Siprotec 7SD5, were tested separately for communication-assisted distance protection and differential protection. A case study was considered where m-SSSC with a reactive power rating of 80 MVAr per phase was placed on a 220 kV transmission line. Relevant HIL simulation cases were considered for grid faults, with and without m-SSSC operation.

2. Modular SSSC Technology

The modular, Static Synchronous Series Compensator (m-SSSC) is a transformerless, self-powered, single-phase FACTS technology [2], [7] that connects in series with existing utility overhead line circuits, and injects a leading or lagging voltage in quadrature with the line current, as shown in Fig. 1, resembling an effective capacitance or inductance respectively. Effective capacitance or inductance increases or decreases energy flow across a transmission line.

A schematic presentation of a single-phase m-SSSC is shown in Fig. 2. It acts as a solid-state synchronous voltage source, consisting of a series of full H-bridge voltage-source converters. Each converter employs a DC capacitor, Insulated Gate Bipolar Transistor (IGBT) switches and antiparallel diodes. A Phase-Locked Loop (PLL) controller per converter monitors the phase of the line current, while a DC voltage controller controls the DC link voltage and ensures that the requested voltage injection is met. Current transformers are used for power harvesting and current sensing.

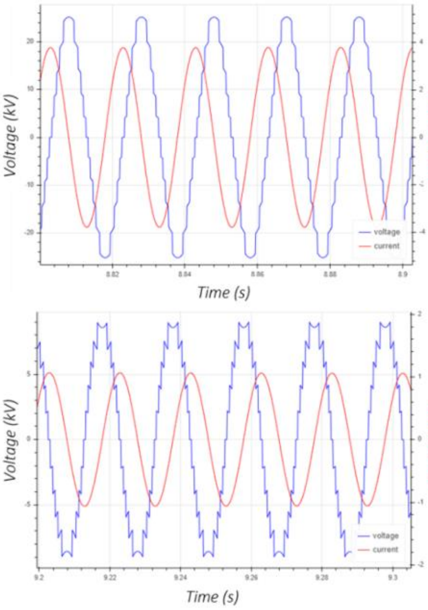

Fig. 1: Example voltage injection in quadrature with line current. Top: Capacitive injection; Bottom: Inductive injection.

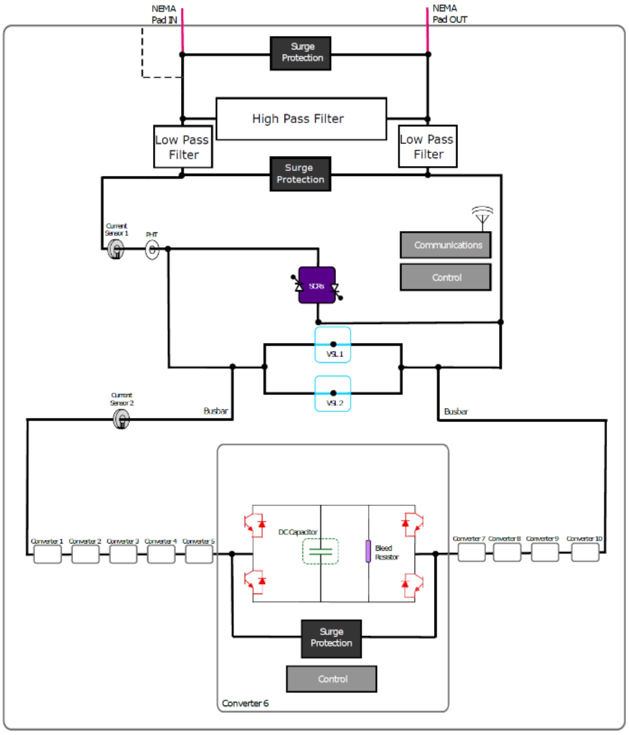

Fig. 2: Schematic presentation of a single-phase m-SSSC.

The m-SSSC system incorporates an instantaneous Over-Current (OC) protection feature. An integrated fast-acting bypass is triggered if any phase current is larger than a pre-programed (and user-selected) threshold; thus, it removes the voltage injection from the system [8]. The bypass is composed of a normally-closed Vacuum Switch Link (VSL) and fast-acting Silicon Controlled Rectifier (SCR) branches that, primarily, conduct the current during grid faults. The bypass occurs within 1 ms from when a current threshold level is exceeded. Thus, the bypass feature minimizes the risk of interactions with existing protection schemes.

M-SSSCs are inherently single-phase devices, and each phase monitors the magnitude and phase of the line current independently. An interphase balancing feature can be enabled for asymmetrical faults, whereby devices on healthy phases ramp down after the fault, and eventually bypass to avoid unbalanced operation.

Due to their modular nature, multiple m-SSSC devices can be connected in series in each phase to create an m-SSSC system with higher compensation capabilities.

The m-SSSC devices have three modes of operation:

1) Monitoring Mode: The m-SSSC system is bypassed.
2) Fixed Voltage Mode: The m-SSSC system is set to output a fixed voltage injection that is either capacitive or inductive, irrespective of the line current.
3) Fixed Reactance Mode: The m-SSSC system is set to output a fixed reactance that is either capacitive or inductive. The injected voltage will vary as the RMS line current changes, to keep the effective reactance at a set value in this control mode.

3. Case Study

A. M-SSSC Rating

A 65.5 km long, 220 kV transmission line is discussed, with a thermal limit rated at 920 A. Furthermore, the load encroachment of distance protection is set at 85 Ω, yielding 1494 A RMS. Several grid operating conditions at N-1 and N-2 show severe overloading of the discussed line. Therefore, an operation of an m-SSSC in series with the discussed line may be used to handle such operating conditions.

Fig. 3 presents the m-SSSC's voltage and reactance operating continuous range against the RMS line current. The orange boundary of the voltage operating range represents the limits for the injected voltage, which can be varied independently of the line current within the range indicated by the gray area. The maximum output voltage is 5660 V RMS per device, inductive or capacitive. The orange boundary of the reactance operating range reflects the effective reactance of an individual m-SSSC available, and the gray area inside reflects the range available when the output voltage varies within the voltage operating range. The m-SSSC can be controlled to maintain a fixed reactance, since the injected voltage can be controlled as a function of the line current.

The discussed m-SSSC model has a reactive power rating of 10 MVAr per single-phase device and a maximum continuous current rating of 1800 A RMS. The entire m-SSSC system consists of 8 devices connected in series at line potential, yielding a total maximum voltage injection of 45280 V RMS per phase, inductive or capacitive. Thus, the reactive power rating of the entire m-SSSC system is 80 MVAr per phase.

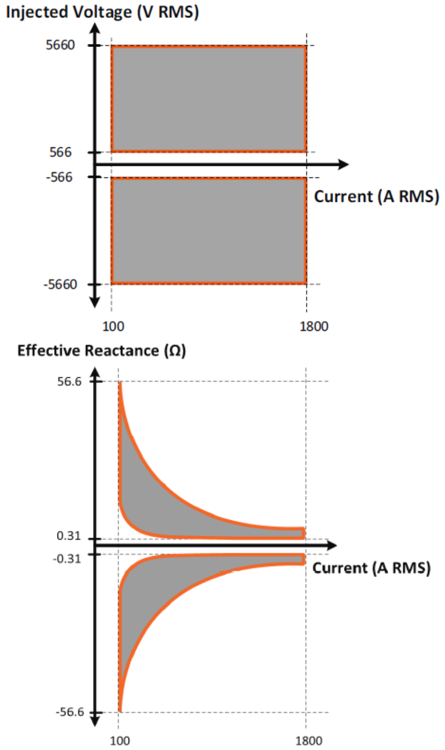

Fig. 3: M-SSSC operating range against the RMS line current. Top: Injected voltage; Bottom: Effective reactance.

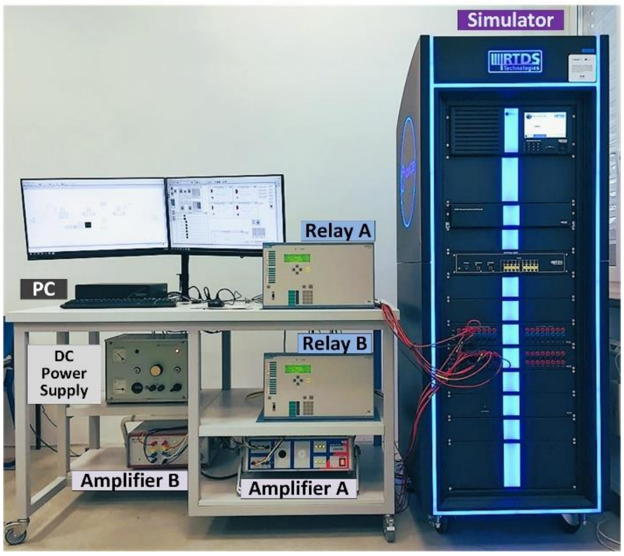

Fig. 4: Protection-In-the-Loop configuration.

Furthermore, the discussed m-SSSC system at maximum injected voltage and maximum current provides an equivalent reactance of 25.1 Ω per phase, while, at a thermal limit of 920 A, the system can provide a reactance of 49.2 Ω per phase.

B. Protection-In-the-Loop Configuration

A real-time NovaCor digital simulator was used to simulate relevant grid faults. The m-SSSC system was located at side A, towards the line, and was represented by an EMT model that was fully validated against the real device (using a Control HIL configuration). Simulations were performed with a step size of 32.25 μs. Two protection relays on each side (A and B) of the line model were connected to the simulator in a closed-loop. The secondary line currents and voltages fed each relay through voltage and current amplifiers and the simulator's AO cards. The relays' binary outputs for a single-phase tripping were fed back to the simulator's DI cards to disconnect the circuit breakers in the model. The operation of two numerical relays, Siemens Siprotec 7SD5, was tested separately for a PUTT communication-assisted distance protection and differential protection. Fig. 4 shows the Protection-In-the-Loop configuration.

C. Overcurrent Threshold Setting of the M-SSSC

A fast-acting bypass is activated when the instantaneous line current exceeds the OC threshold I_{th}. Appropriate selection of the OC threshold is highly important, in order to ensure that (i) The m-SSSC does not bypass during normal operating conditions; (ii) The risk of the distance protection relays operating while the m-SSSC system is not bypassed is minimal; and (iii) The m-SSSC bypass is triggered under minimum short-circuit current conditions.

To satisfy the above requirements, the following methodology was considered, i.e.,

$$I_{\mathrm{th}} > 1.5\sqrt{2}\, I_{\mathrm{Lmax}} \tag{1}$$

$$I_{\mathrm{th}} < \sqrt{2}\, I_{\mathrm{encroach}} \tag{2}$$

$$I_{\mathrm{th}} < 0.75\, I_{\mathrm{SCmin}} \tag{3}$$

Table I: Peak short-circuit currents on both sides of the line.

		I_A [kA]		I_B [kA]	
SCC	Fault Loc.\Type	3-Ph	Ph-G	3-Ph	Ph-G
min	Busbar A	13.7	11.3	4.7	3.1
	Busbar B	4.2	3.0	26.3	15.0
max	Busbar A	23.8	25.5	4.9	4.0
	Busbar B	4.9	3.4	36.8	19.2

where I_{Lmax} is the rated RMS line current (thermal limit), I_{encroach} is the RMS line current corresponding to load encroachment of the distance protection, and I_{SCmin} is the minimum peak short-circuit current.

Table I shows the peak short-circuit currents seen on both sides of the discussed line for three-phase (3-Ph) and phase-to-ground (Ph-G) faults at both busbars, and for the minimum and maximum short-circuit capability (SCC) of the aggregated network supplies.

Considering $I_{\mathrm{Lmax}} = 920$ A RMS, $I_{\mathrm{encroach}} = 1494$ A RMS and $I_{\mathrm{SCmin}} = 3$ kA peak, inequalities (1)–(3) suggest that 1.95 kA < I_{th} < 2.11 kA. Therefore, the m-SSSC OC threshold for this analysis was set at 2 kA peak.

D. M-SSSC Failure Modes

A desktop analysis was carried out to investigate the potential impact of m-SSSC failures on the operation of the protection systems. The following failure modes were considered:

1. Interphase balancing (communications) failure during a Ph-G fault, i.e., the bypass is triggered only in one phase, while the other two phases continue to inject.
    - When interphase balancing is triggered, a ramp-down signal is sent to the healthy phases. This means that the injection is decreased gradually before transitioning to Monitoring Mode, and is not removed from the system instantly. Hence, an interphase balancing failure is not expected to affect the relay operation within the protection timescales.
2. Bypass failure of a single device, where one device (out of eight) keeps injecting.
    - The m-SSSCs are highly redundant devices with multiple methods of detecting a fault and interrupting injection. To continue injecting during a fault, it would require multiple successive failures within different sub-systems, which would have to materialize at the same time as the fault occurrence.

Based on this risk assessment exercise, it was not deemed necessary to consider such scenarios and include additional study cases as part of this paper.

4. Test Cases and Results

This section investigates the impact of an m-SSSC on the operation of the transmission line protection relays using a laboratory HIL configuration (Section 3-B). All tests were performed for two m-SSSC operating modes: (i) Monitoring Mode, where the m-SSSC system is bypassed (further denoted as "without m-SSSC"); and (ii) Fixed Voltage Mode, where the level of injection by the m-SSSC system was 15 kV RMS inductive per phase (hereinafter "with m-SSSC"), while the OC threshold level for the fast-acting bypass was set at 2 kA peak.

A. Grid Faults

A short-circuit study for the grid, which is electrically close to the discussed 220 kV line, showed that the m-SSSC's bypass was triggered only during faults located on the line or at both 220 kV busbars. In cases of faults applied to other transmission lines and busbars at 400, 220 and 110 kV levels, the m-SSSC's bypass was, expectedly, not triggered, since the resulting fault currents were below the OC protection threshold. The same was also observed for the line distance and differential protection schemes.

Therefore, only faults on the discussed 220 kV line were simulated, considering the following characteristics:

- Fault type: 3-Ph, Ph-Ph, Ph-Ph-G and Ph-G.
- Fault location: 5, 50 and 95% (from side A).
- Fault inception angle: 0, 45 and 90 degrees (phase L1).
- Fault resistance: 0, 10 and 50 Ω.

Furthermore, all fault cases were simulated separately for the following operating conditions of the grid:

- Minimum and maximum SCC of the aggregated network supplies A and B (Table I).
- Pre-fault energy flow value corresponding to approx. 900 A without an m-SSSC.
- Pre-fault energy flow direction from A to B and from B to A.
- Differential protection enabled/disabled (distance protection only and distance protection + differential protection).

Based on the combination of the above scenarios, the total number of simulated test cases amounted to 1728.

C. Results

Figs. 5 and 6 show the time responses of line currents and voltages captured at relay A i_{REL} and u_{REL}, respectively, injected line voltages by the m-SSSC system u_{mSSSC}, and single-phase tripping commands of relay A. A solid fault was simulated in the middle of the line, with a fault inception angle in phase L1 of 0 deg. Note, the fault inception time in Figs. 5 and 6 was set to zero for clarity.

Fig. 5 shows the results for a 3-Ph fault, where the m-SSSC system stops injecting in each phase within 1 ms from when the OC threshold level was exceeded. The trip time of the relay was approximately 25 ms (in each phase), while the fault was cleared after the operation of the circuit breakers on both sides (A and B). The results for a Ph-G fault are shown in Fig. 6, where the m-SSSC system stops injecting only in the faulted phase L1, while the relay also trips only in phase L1 with a delay of approximately 25 ms. The fault was cleared only in phase L1 from both sides (A and B), where a residual voltage in phase L1 was due to the mutual and ground capacitances of the transmission line model. Furthermore, injection by the m-SSSC system in the healthy phases L2 and L3 was ramped down slowly to a minimum injection value, after which the m-SSSC system stopped injecting (driven by the interphase balancing feature).

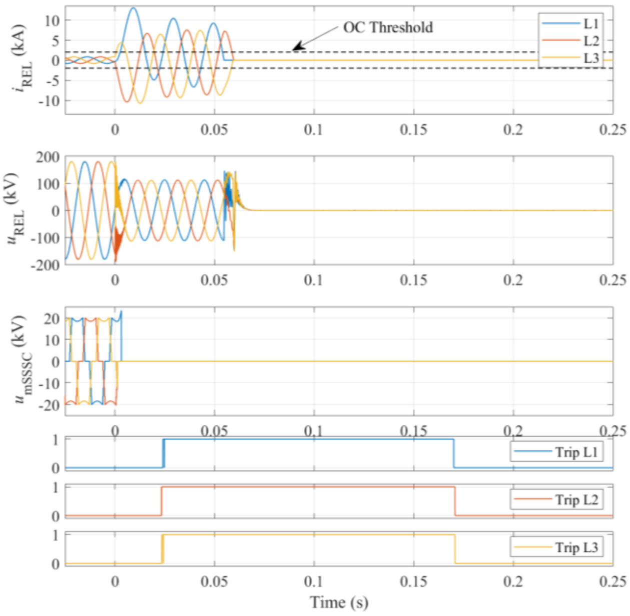

Fig. 5: Time responses measured on side A during a solid 3-Ph fault test.

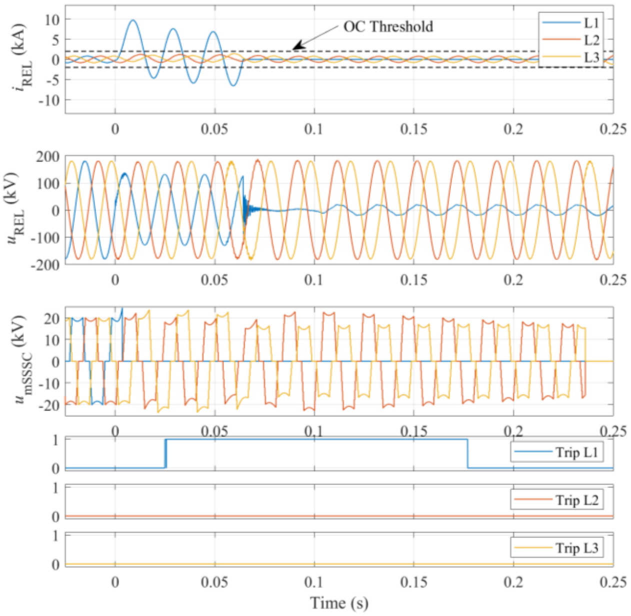

Fig. 6: Time responses measured on side A during a solid Ph-G fault test.

Fig. 7 shows the measured distance protection trip times, i.e., with the m-SSSC (Fixed Voltage Mode) versus without the m-SSSC (Monitoring Mode) for all the discussed grid faults, as described in Section 4-A. Furthermore, results are also shown for different directions of the pre-fault energy flow and the minimum and maximum SCC of the aggregated network supplies.

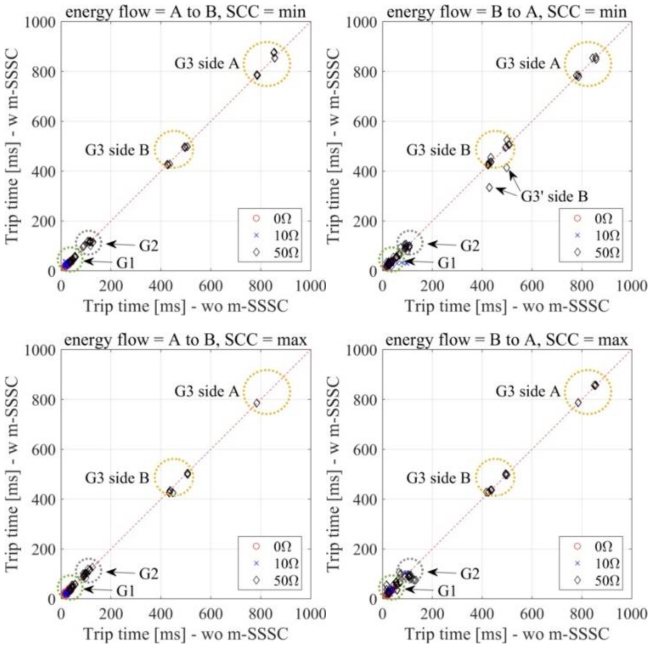

Fig. 7: Measured distance protection trip times with (w) and without (wo) the m-SSSC with denoted groups G1-G3.

The results in Fig. 7 are shown only for the distance protection operation in zones 1 and 2. Note that zone 1 was set without delay, while the delay time of zone 2 was set as 0.75 s on side A and as 0.4 s on side B. Furthermore, all the resulting trip times can be divided into six groups, as follows:

G1: Trip times were shorter than 80 ms, regardless of the grid and fault conditions, while the m-SSSC system did not affect the protection operation.

G2: Trip times were in an interval of 80 to 130 ms, which is still acceptable, and both relays operated in zone 1. There were rare cases for 3-Ph and Ph-Ph faults, where operation with the m-SSSC shortened the trip times to 30 ms.

G3: This group contains only cases with 50 Ω fault resistance, where both relays operated in zone 2. The M-SSSC operation (with or without the m-SSSC) did not affect the protection operation in most of the cases of 3-Ph and Ph-Ph faults. Furthermore, this group also contains cases of Ph-G faults, where operation with the m-SSSC shortened the trip times of relay B by 100 ms (subgroup G3').

G4: In rare cases of Ph-Ph faults with 50 Ω resistance, both relays operated in zone 3 when the grid operated without the m-SSSC. However, when the grid operated with the m-SSSC, relay B operated in zone 2.

G5: A single case of a Ph-G fault with 50 Ω resistance, where both relays operated in zone 2 when the grid operated without the m-SSSC. However, when the grid operated with the m-SSSC, the trip time of relay A was further delayed by approx. 280 ms

G6: Rare cases of Ph-Ph faults with 50 Ω resistance, where both relays operated in zone 3 due to the low fault currents, regardless of m-SSSC operation.

The measured differential protection trip times were between 10 to 25 ms regardless of the grid and fault conditions, while the m-SSSC did not affect protection operation.

5. Conclusion

This paper presents the results of real-time tests of communication-assisted line distance and differential protection relays of a 220 kV transmission line equipped with an m-SSSC using an HIL configuration. 1728 simulations were carried out, considering exhaustive combinations of grid faults and m-SSSC operating modes. The m-SSSC OC threshold was selected carefully, such that the risk of affecting the operation of the distance protection relays is minimal.

The main conclusions of this work can be summarized as follows:

1. The m-SSSC fast-acting bypass performed as expected, triggering transition to the Monitoring Mode within 1 ms of any phase current exceeding the pre-programed OC threshold. It therefore removes the injected voltage from the system quickly enough to prevent unwanted interactions with distance protection schemes.
2. Delayed operation of distance protection relays was noticed for some high-resistive faults, regardless of the operation of the m-SSSC system. It should be noted that distance protection relays are not the most appropriate to detect high-resistive faults.
3. In rare cases of high-resistive faults, the m-SSSC system affects distance protection operation. This difference is attributed to the fact that the m-SSSC voltage injection changes the pre-fault steady-state operating conditions. Nevertheless, the relay trip times were shortened in the vast majority of these scenarios.
4. Differential protection operation was, expectedly, not affected by the m-SSSC system, and acted as back-up protection where required.
5. The overall risk of an m-SSSC operation introducing an adverse effect on the transmission line protection systems is deemed negligible.

The discussed m-SSSC technology is adopted increasingly by transmission system operators around the world due to proven system benefits [9]. This paper offers useful insights into the m-SSSC operating principles during grid faults. The Protection-In-the-Loop study results can increase the confidence of both transmission owners and system operators over the m-SSSC technology to provide dynamic energy flow control without introducing unacceptable risks to the system.

References

[1] N. G. Hingorani, L. Gyugyi, “Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems”, Wiley-IEEE Press, Piscataway, NJ (1999).

[2] ENTSO-E, Technopedia: Static Synchronous Series Compensator

(https://www.entsoe.eu/Technopedia/techsheets/static-synchronous-series-compensator).

[3] D. Ingole, V. Gohokar, “Voltage Stability Improvement In Multi-bus System Using Static Synchronous Series Compensator”, Energy Procedia (2017), vol. 117, pp. 999-1006.

[4] M. A. K. Aziz Biabani, et al, “Power system stability enhancement using static synchronous series compensator”, International Conference on Signal Processing, Communication, Power and Embedded System, Paralakhemundi, India, 2016.

[5] T. Rajaram, J. M. Reddy, Y. Xu, “Kalman Filter Based Detection and Mitigation of Subsynchronous Resonance with SSSC”, IEEE Transactions on Power Systems (2017), vol. 32, 99. 140-1409.

[6] L. J. Kovalsky, et al., “Study Results of the Impact of a Modular SSSC to Transmission Line Protection Schemes”, CIGRE US National Committee 2018 Grid of the Future Symposium.

[7] A. C. Stratigakos, et al., “Experience Gained from Deploying Mobile Modular Power Flow Control Technology on the Greek Power System”, 3rd SEERC Conference, Vienna, Austria, 2020.

[8] R. Fenlon, “An application of modular FACTS devices to relieve transmission constraints and accelerate wind farm connections and firm access”, Wind Integration Workshop, Dublin, 2019.

[9] H. Kaouk and P. Xenos, “Modular Static Synchronous Series Compensators for the Future Power System in the SEERC Region”, CIGRE South East European Regional Council Colloquium 2021, November 2021, paper no: 1239.