B&H Electrical Engineering, Volume 19, Issue 2, 2025
ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2025-0012

Original scientific paper

Submitted: March 16, 2025

Accepted: October 1, 2025

HARDWARE-IN-THE-LOOP TESTING AND ANALYSIS OF RAPID VOLTAGE INJECTION ON TRANSMISSION LINES USING MODULAR SSSC WITH LINE DISTANCE PROTECTION SECURITY CONSIDERATIONS

Boštjan Polajžer[1,4], Jernej Černelič[1], Uroš Kerin[3], Gorazd Hrovat[2]

Abstract: ELES, ltd., is the combined transmission and distribution system operator of Slovenia. It operates 110 kV, 220 kV and 400 kV networks and has strong tie lines with transmission grids of Austria, Croatia, Hungary and Italy. As part of the ongoing efforts to ensure transmission system stability as well as operational flexibility under continuously changing conditions, advanced FACTS devices are being implemented into the grid. Installation of a Static Series Synchronous Compensator (SSSC) on a 220 kV interconnection line will help prevent internal bottle-necks and potential cascading events due to a loss of an interconnection line on the Slovenian – Austrian border. SSSC is a fast-acting device with rapid response capability for controlling power flow. Because local actions can quickly impact regional situations, it is essential to thoroughly consider all operational aspects during the feasibility assessment, design, and pre-engineering phases. This paper investigates the rapid voltage injection on a transmission line provided by a modular SSSC (m-SSSC) during a sudden increase in line currents. A case study for an m-SSSC with a rated reactive power of 80 MVAr per phase is considered. The adopted m-SSSC model was tested with electromagnetic transient (EMT) simulations. A sudden increase of the line currents corresponding to an N-2 event was simulated for various cases. The analysis of the m-SSSC responses shows the dynamic characteristics of the current override feature, which ensures rapid voltage injection. Special attention has been paid to the security of line distance protection operation, where hardware-in-the-loop simulation cases, with and without m-SSSC operation, have been considered. Two Siemens Siprotec 7SD5 numerical relays were tested using communication-assisted distance protection. The results show that the considered m-SSSC can prevent non-selective distance protection operation during such N-2 events.

Keywords: FACTS, Static Synchronous Series Compensator, Protection-In-the-Loop, Distance Protection

INTRODUCTION

ELES, ltd., is the combined transmission and distribution system operator of Slovenia. It operates 110 kV, 220 kV, and 400 kV networks and has strong tie lines with transmission networks in Austria, Croatia, Hungary, and Italy. The principal network topology is shown in Fig. 1. As part of the ongoing efforts to ensure transmission system stability as well as operational flexibility under continuously changing conditions, advanced FACTS devices are being implemented on the network. Installation of a Static Series Synchronous Compensator (SSSC) on a 220 kV interconnection line will help prevent internal bottle-necks and potential cascading events due to a loss of a 400 kV interconnection line on the Slovenian–Austrian border.

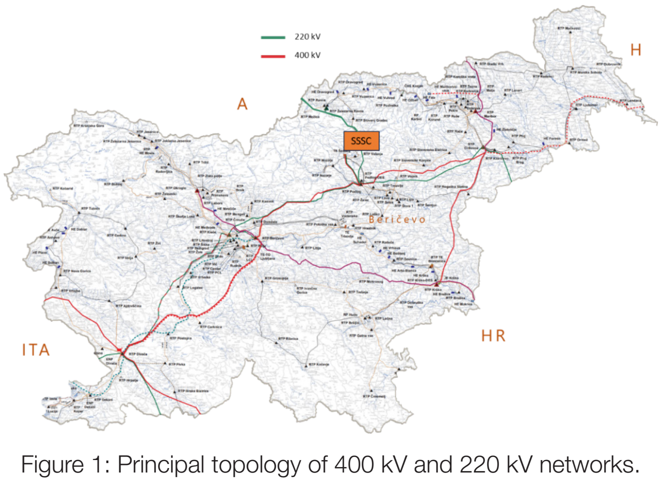

Figure 1: Principal topology of 400 kV and 220 kV networks.

The 400 kV and 220 kV tie lines between Slovenia and Austria are essential for facilitating international power flows and electricity market coupling. However, they are occasionally subjected to high loading, bringing the network closer to potentially critical conditions. To

This paper was submitted to the Conference of the South-East European Regional Council of CIGRE (SEERC 2025), held in Sarajevo, Bosnia and Herzegovina, on June 4–5, 2025.

[1] *University of Maribor, Faculty of Electrical engineering and Computer Science, Slovenia*
[2] *ELES, d.o.o., Slovenia*
[3] *Milan Vidmar Electric Power Research Institute, Slovenia*
[4] *Correspondence email: bostjan.polajzer@um.si*

manage power flow and prevent excessive loading, various operational measures can be applied, including line switching or busbar decoupling. While these manoeuvres can be effective in daily operations, they should not become standard practice, as they reduce the system's flexibility to respond to contingency situations. Instead, specialized equipment should be installed and integrated into system control strategies, such as phase-shifting transformers or FACTS devices. A typical example of a FACTS device with such capabilities is the SSSC [1], [2]. It can be used to adjust the equivalent line impedance, thereby increasing or decreasing the active power transfer capacity of the line. Highly controllable, the SSSC offers functionalities and services to the energy system that go beyond those of a phase-shifting transformer and other network elements with discrete control capabilities.

1. MODULAR SSSC TECHNOLOGY

The modular, Static Synchronous Series Compensator (m-SSSC) is a single-phase, transformerless, and self-powered FACTS technology [3-6]. It connects in series with a transmission line and injects a leading or lagging voltage in quadrature with the line current, thus effectively adjusting capacitance or inductance to change the energy flow. Multiple m-SSSC devices can be connected in series to create an m-SSSC system with higher compensation capabilities. M-SSSC operates as a single-phase solid-state synchronous voltage source; a schematic presentation is s depicted in Fig. 2. It consists of a series of full H-bridge voltage-source converters, each employing a DC capacitor, Insulated Gate Bipolar Transistor (IGBT) switches, and

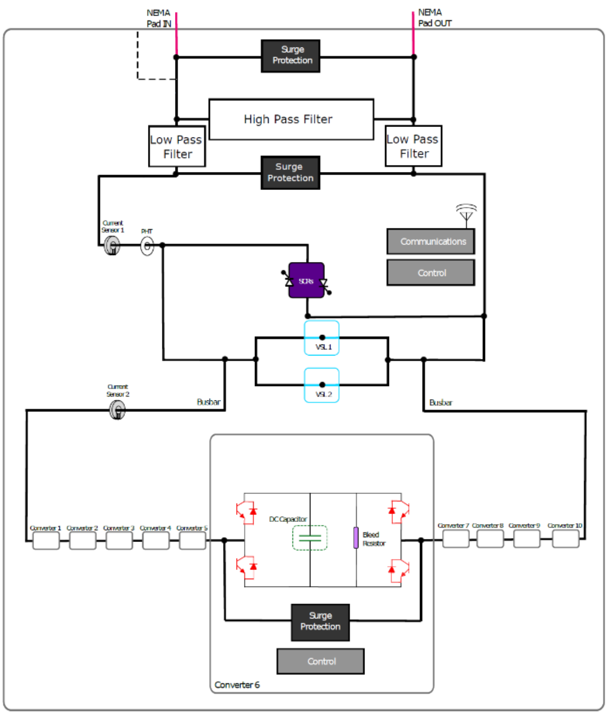

Figure 2: Schematic presentation of a single-phase m-SSSC.

antiparallel diodes. A DC voltage controller controls the DC link voltage and ensures that the requested voltage injection is met. A Phase-Locked Loop (PLL) controller per converter monitors the phase of the line current, while current transformers are used for power harvesting and current sensing.

Furthermore, an integrated fast-acting bypass removes the voltage injection with a short-circuit path when the line current reaches a configurable threshold. In this way, the risk of interactions with existing line protection schemes is minimized. The bypass comprises a normally-closed Vacuum Switch Link (VSL) and fast-acting Silicon Controlled Rectifier (SCR) branches. An interphase balancing feature can be enabled for asymmetrical network faults, whereby devices on healthy phases ramp down and eventually bypass to avoid unbalanced operation. Once the line currents fall below the threshold for a configurable time, the m-SSSC device begins injecting again. The m-SSSC system has the following control modes:

0) Monitoring Mode: The m-SSSC system is bypassed.
1) Fixed Voltage Mode: The m-SSSC system is set to output a fixed voltage injection that is either capacitive or inductive, independently of the line current.
2) Fixed Reactance Mode: The m-SSSC system is set to output a fixed reactance that is either capacitive or inductive. In order to keep the set effective reactance, the injected voltage will change as the RMS line current varies.
3) Automatic Current-Control Mode: The m-SSSC system can automatically start or stop injecting voltage based on the energy flow.

Two deployments of the m-SSSC technology in ENTSO-E networks can be mentioned, i.e., in Great Britain and Spain. As outlined in [3], pilot deployments have also been carried out in Greece and Bulgaria.

This paper investigates the Current Control Override (CCO) feature that overrides the selected Monitoring, Fixed Voltage, or Fixed Reactance control mode if the current exceeds a pre-configured threshold. In this case, the system will ramp up inductive voltage injection to limit the current according to the configurable droop characteristic, as shown in Fig. 3.

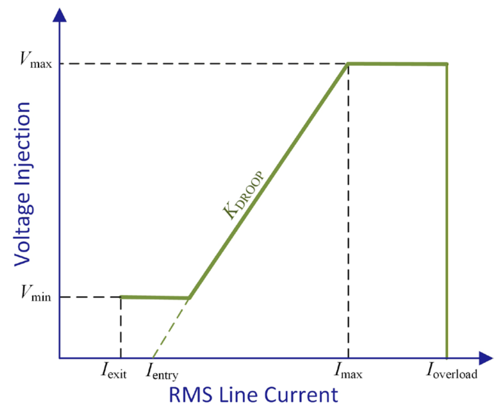

Figure 3: Configurable droop characteristic of the CCO feature.

The CCO feature operation is explained as follows:

- If enabled, the CCO feature is automatically activated once the RMS line current exceeds the parameter I_{entry} for a time delay given by the (T_1+T_2) parameters.
- At this point, the m-SSSC system begins injecting inductively with a proportional relationship given by the parameter K_{DROOP}. The CCO feature aims to manage the line current between configurable parameters I_{entry} and I_{max}.
- The m-SSSC system reaches its maximum output at I_{max} and cannot provide higher injections than V_{max} even if the line current increases further.
- If the RMS line current drops below I_{exit} for a time equal to T_1, the m-SSSC system will return to its previous mode of operation. I_{exit} setting is provided through an offset from I_{entry}.
- If the line current is between I_{entry} and I_{exit}, the minimum voltage injection V_{min} will be provided.

The Fast Ramp Rate (FRR) functionality can also control rapid voltage injection. Here, the configurable parameters are the duration for which the injection rate stays applicable and the maximum fast rate of charge and discharge of the DC Link voltage of a single converter.

2. CASE STUDY

The 220 kV interconnector at the Slovenian-Austrian border is under consideration. The line length is 65.5 km, and the thermal limit is 960 A on the Slovenian side and 920 A on the Austrian side. Several N-1 and N-2 operating conditions in the network indicate severe overloading of the discussed line in the direction from Austria to Slovenia, which may even exceed 300% of the thermal limit. The distance protection will operate during such events as its load encroachment corresponds to 1690 A at nominal voltage. Therefore, an operation of an m-SSSC in series with the discussed line is considered to handle such operating conditions by rapid voltage injection through the CCO feature.

The rated reactive power of the discussed m-SSSC system is 80 MVAr per phase, which requires eight single-phase modules with a maximum continuous rated current of 1800 A and a maximum output voltage of 5660 V. Thus, the total maximum voltage injection is 45280 V per phase, inductive or capacitive. This means that the m-SSSC system under consideration can provide an equivalent reactance of 25.2 Ω per phase at the maximum injected voltage and maximum current.

The NovaCor real-time digital simulator was used to simulate the N-2 event (loss of a 400 kV interconnector with Austria) corresponding to a sudden increase in line currents from approximately 500 A to 1800 A. Dynamic load was used to simulate the change in line currents and to maintain the voltages within the ±10% of the nominal value. The m-SSSC was placed on the Slovenian side towards the line and was represented by an EMT model. Two Siemens Siprotec 7SD5 protection relays were connected to the simulator on each side of the line model (Slovenia and Austria). The simulated secondary line currents and voltages fed each relay through voltage and current amplifiers and the simulator's AO cards. The relays' binary outputs were fed back to the simulator's DI cards to disconnect the circuit breakers in the model. Real-time simulations were carried out with a step size of 64.5 μs. Fig. 4 shows the Protection-In-the-Loop configuration.

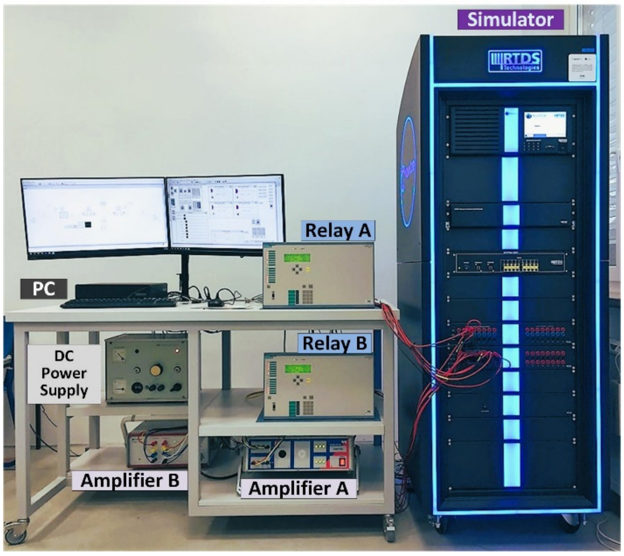

Figure 4: Protection-In-the-Loop configuration.

The droop gain of the CCO feature was calculated as given by (1). All the relevant parameters of the CCO features are given in Table I, where K_{DROOP} is given for the I_{entry} value corresponding to the thermal limit of 960 A. Note that T_1 is a configurable delay before the m-SSSC system transitions into and out of CCO mode. Since the injection before the activation of the CCO mode can be capacitive, additional time delay is introduced for a smooth transition, i.e., $T_2 = 2T_1$. Thus, the total injection delay is given as (T_1+T_2) = 0.9 s.

$$K_{Droop} = \frac{V_{max}}{(I_{max} - I_{entry})} \tag{1}$$

Table I: Relevant parameters of the CCO feature.

V_{max} [V]	I_{entry} [A]	I_{exit} [A]	I_{max} [A]	T_1 [s]	K_{DROOP} [V/A]
45280	920 or 960	200	1800	0.3	53.9

A communication-assisted distance protection was tested on both sides of the discussed 220 kV line. Parameters of the distance protection in higher zones are given in Table II, but only for the Slovenian (SI) side and Phase-to-Phase (Ph-Ph) faults. Zone 3 is directional and operates for the current flowing from the busbar to the line, while zone 4 is non-directional. Furthermore, load encroachment was set to 150% of the thermal limit at 85% of the nominal voltage. Note that parameters for the Austrian (AT) side are slightly different and are not given for confidentiality reasons; however, they were used during the testing.

Table II: Relevant distance protection Ph-Ph settings for the Slovenian side.

	R [Ω]	X [Ω]	T_{delay} [s]	angle [deg.]
Zone 3	76.7	76.7	2	-
Zone 4	85	85	4.8	-
Load enc.	75	-	-	±30

Minimal and maximal short-circuit capability (SCC) of the aggregated network supplies on both sides of the line were used in the simulations. Table III shows short-circuit currents on both sides of the discussed line for three-phase faults at both busbars.

Table III: Short-circuit currents on both sides of the line.

SCC	Fault Loc.	I_{SI} [kA]	I_{AT} [kA]
min	SI	9.688	3.323
	AT	2.970	18.5997
max	SI	16.829	3.465
	AT	3.465	26.022

3. RESULTS

This section first analyses the dynamic and steady-state behaviour of the CCO feature during simulations of an N-2 event. Simulations were performed for minimal and maximal SCC of the supply, different durations of the FFR functionality T_{FFR}, and different values of the parameter I_{entry}. The droop gain was the same in all the cases, i.e., K_{DROOP}= 53.9 V/A. Fig. 5 shows waveforms of simulated line currents and injected line voltages for minimal SCC, I_{entry}= 960 A and T_{FFR}= 0.2 s. At a simulation time of 2 s, the N-2 event was simulated, and line currents rapidly increased from approximately 500 A RMS to 1800 A RMS. The m-SSSC system starts injecting via the CCO feature; the delay and settling times are denoted as t_{delay} and t

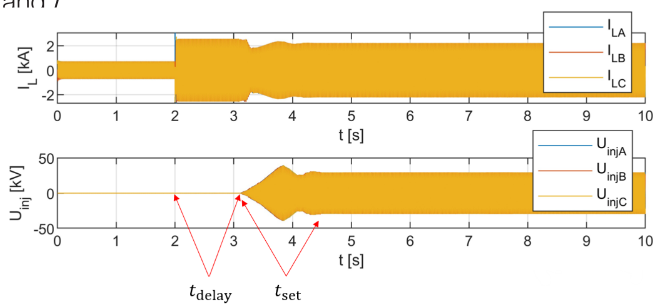

Figure 5: Time responses of line currents' and injected voltages' waveforms during N-2 event simulation and CCO activation.

In order to thoroughly analyze the obtained time responses, the steady-state RMS value of line currents, injected voltages, and effective reactance were measured along with the time delay and settling time. Results for all the discussed cases are given in Table IV. The injected voltages are higher for the minimal SCC of the supply, and the resulting reactances are larger than for the maximal SCC of the supply. The largest reduction of the line currents is achieved for the maximal SCC and the lowest value of the parameter I_{entry}. However, in all the cases, line currents were reduced below the value corresponding to the distance protection load encroachment, which is for the nominal line voltages given as 1.69 kA. Delay time T_{FFR} had practically no effect on the responses, and the measured delay and settling times (t_{delay}+t_{set}) of the responses ranged between 1.88 s and 2.71 s, with a median of 2.49 s. The model produced asymmetrical injections in one case (marked in red in Table IV). Moreover, additional testing for the increased parameter K_{DROOP} indeed resulted in a larger reduction of line currents, but responses were less damped, and settling and delay times were larger.

Table IV: Results of an OCC feature for different test cases.

SCC	I_{entry} [A]	T_{FFR} [s]	I_L [kA]	V_{inj} [kV]	X_{mSSC} [Ω]	t_{delay} [s]	t_{set} [s]
max	920	0	1.31	20.93	15.98	1.11	1.38
max	920	0.2	1.43/ 1.31	14.34/ 21.74	10.03/ 16.6	-	1.44
max	920	1	1.31	20.98	16.02	1.06	1.23
min	920	0	1.55	33.78	21.79	1.12	1.59
min	920	0.2	1.55	33.8	21.81	1.16	0.72
min	920	1	1.55	33.8	21.81	1.17	0.8
max	960	0	1.34	19.92	14.87	1.1	1.39
max	960	0.2	1.33	20.01	15.05	1.07	1.57
max	960	1	1.33	20.05	15.08	1.06	1
min	960	0	1.57	32.94	20.98	1.11	1.55
min*	960	0.2	1.57	32.74	20.85	1.12	1.41
min	960	1	1.57	32.95	20.99	1.13	1.39

Legend: Fig. 5 shows time responses for the case denoted by *; The case coloured in red showed asymmetric injections; Cases coloured in dark green were used for HIL protection testing.

In the rest of this section, the impact of an m-SSSC on the operation of the line distance protection is investigated using a laboratory Protection-In-the-Loop configuration. First, the tests were performed for the bypassed m-SSSC system (further denoted as "without m-SSSC"), and then the CCO feature was tested for the two cases from Table IV marked in dark green (further denoted as "with m-SSSC & CCO"). Moreover, both directions of the energy flow were simulated, i.e., AT to SI and SI to AT.

Results of distance protection operation are given as impedance trajectories in the R - jX plane, as recorded by

ISSN:2566-3143, eISSN:2566-3151, DOI: 10.2478/bhee-2025-0012

a relay. Note that the secondary impedances are shown, where the voltage and current transformer ratios were 2000/1 A and 220/0.1 kV, respectively. Thus, the relation between the primary and secondary impedance is given as $Z_{sec}=Z_{prim}/1.1$.

Distance protection operation for the cases without m-SSSC was as expected, i.e., the relay disconnected the line with the time delay of zone 3 when the energy flow was from the busbar to the line. Consequently, the relay on the opposite side of the line only picked up in zone 4. Cases with m-SSSC & CCO prevented the operation of the distance protection on both sides of the line, and only pick-up was recorded on both relays due to the delayed injection of the m-SSSC system. Fig. 6 shows impedance trajectories (secondary values) measured by the relay at the SI side for energy flow AT to SI and maximal SSC of supply. Measured values are in the second quadrant since the energy flow is from the line to the busbar. An orange marker shows impedance settled in zone 4 after the increase in line currents. In the case without m-SSSC, the impedance stayed in zone 4 (Fig. 6a), while in the case with m-SSSC & CCO, the impedance moved outside the zone, denoted by a blue marker (Fig. 6b). Impedances measured by the relay at the AT side are not shown for confidentiality reasons. The obtained results confirmed the correct setting of the CCO feature for the energy flow AT to SI.

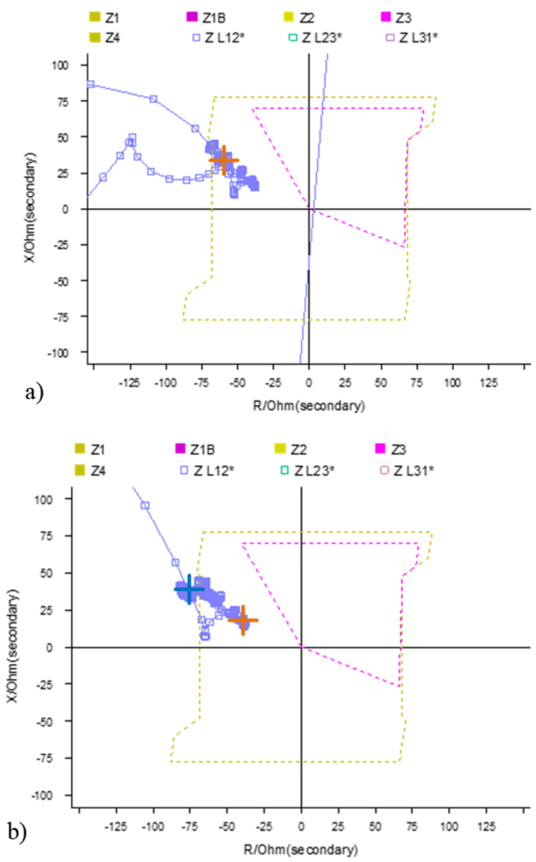

Figure 6: Trajectories of a Ph-Ph secondary impedance measured by a relay at SI side for energy flow AT to SI and maximal SSC of supply: without m-SSSC (a), with m-SSSC & CCO (b).

In cases of energy flow SI to AT, which rarely occurs, the relay at the SI side operated with the time delay of zone 3 despite the CCO feature activation. An alternative solution for such cases could be activating the m-SSSC injection in the Fixed voltage mode through a relay pick-up signal. Such an activation should be delayed for a time longer than the time delay of the distance protection zone 3.

4. CONCLUSION

SSSC devices are gaining attention in the TSO industry. While they are not yet a widely adopted solution for power flow control, their application has been steadily increasing in recent years, particularly in European networks. ELES, Slovenia's combined transmission and distribution operator, has extensive experience in power flow control at its borders, operating several phase-shifting transformers. By installing an SSSC, the existing FACTS portfolio would be expanded, enabling new control and protection strategies.

This paper examines the impact of a modular SSSC operation on the 220 kV network and potential interactions with line protection relays. Given that the device's response time is in the range of several tens of milliseconds, it is crucial to ensure that its operation does not inadvertently trigger unnecessary tripping or other unintended protection actions. To address this, extensive simulations and hardware-in-the-loop testing were conducted. The results confirmed that no abnormal conditions would arise and that the m-SSSC operation was compatible with the existing relay settings.

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] 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, paper no: 1239, November 2021.

[4] B. Polajžer, A. Trupej, P, Xenos, "Analysis of the Impact of a Modular SSSC on the Operation of Transmission Line Protection Relays using a Hardware-In-the-Loop Configuration", 20th International Conference on Renewable Energies and Power Quality (ICREPQ'22), Vigo (Spain), 27th to 29th July 2022.

[5] D. Barron, et al., "Real Time Dynamic Performance, Control Interaction and Protection Studies of Modular Static Synchronous Series Compensation Technology in the Great Britain Transmission System", Ref B4-10116_2022, CIGRE Paris Session, 2022.

[6] S. Hincapie, et al., "Real-Time Simulations to Validate the Impact of m-SSSC Devices on Protection Coordination in Power Systems", Ref B5-11756-2024, CIGRE Paris Session, 2024.

BIOGRAPHY

Boštjan Polajžer received the B.S. and Ph.D. degrees in Electrical Engineering from the Faculty of Electrical Engineering and Computer Science, University of Maribor, Maribor, Slovenia, in 1997 and 2002, respectively. Since 1998, he has been with the Faculty of Electrical Engineering and Computer Science, University of Maribor, where, since 2010, he has been an Associate Professor. His research interests include electrical machines and devices, power quality, and power-system protection and control.

Jernej Černelič received the B.Sc. and Ph.D. degrees in Electrical Engineering from the Faculty of Electrical Engineering and Computer Science, University of Maribor, Maribor, Slovenia, in 2012 and 2017, respectively. He works as a Researcher and Assistant at the University of Maribor. His research interests include modeling and control of electrical and electromechanical converters and power electronics, as well as power system protection.

Uroš Kerin received the B.Sc. and Ph.D. degrees in Electrical Engineering from the Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia, in 2004 and 2010, respectively. He is a renowned expert in electrical power engineering, digital technologies, and strategic management. He has built his career at the intersection of the research and industrial worlds – from international experience at Siemens PTI and AIT Vienna to leading roles at Slovenian transmission system operator ELES, where he directed digital and energy innovations and built strategic partnerships. He is a director of the Milan Vidmar Electric Power Research Institute.

Gorazd Hrovat received the B.Sc. and Ph.D. degrees in Electrical Engineering from the Faculty of Electrical Engineering and Computer Science, University of Maribor, Maribor, Slovenia, in 2001 and 2006, respectively. Since 2007, he has been employed as a technical expert at Slovenian transmission system operator ELES in the secondary system department. His main area of work includes the calculation of protection settings in transmission networks and fault analysis.