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Innovative grid technologies

Standardized Modelling of Static Synchronous Series Compensator (SSSC) and High-Capacity Superconductor DC cables

CurrENT

Enabling Network Technology throughout Europe

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Executive summary

The European power system is facing unprecedented challenges in its transition to a power system that will be dominated by renewable generation, and that can enable Europe to be the first climate-neutral continent with a modern, resource-efficient economy. Of course, these challenges are not unique to the European power system - every power system in the world is faced with its own transition in order to meet the goals of the Paris agreement. New electricity transmission and distribution technologies are crucial to developing a cost-efficient grid that can support this global transition, as well as the fast development and rollout of Information and Communication Technologies.

In this ever-changing environment, system operators, manufacturers, research and innovation, academia, software development and consultancy services are challenged to jointly pave the way in a complex and continuously evolving power system. In Europe, ENTSO-E has been given an important mandate to facilitate the transition of the power system, with deliverables like the EU network codes and the Ten-Year Network Development Plan (TYNDP), which are among the key instruments to coordinate efforts and stimulate innovation.

Designing, developing and operating a power system is not a trivial task. It needs to be performed carefully, while ensuring the integrity, reliability and stability of the system. Each device, operational decision, and planning study must be consistent and must interact, as there are countless interdependencies. Modelling the power system is of the utmost importance to enable adequate studies and ensuring interoperability among them is key to integrating different technologies, both hardware and software, seamlessly in the power system. There are several standards that should be considered when modelling a power system but due to the transitory nature of the process – the continuous evolution, alignment and improvement - we are also challenged to innovate and enhance these standards to keep them fit-for-use and fit-for-purpose.

As a key industry association representing innovative grid technology companies operating in Europe, currENT is taking Europe’s power network to the next level by developing and supplying innovative technologies that enhance the efficiency of the electricity grid. To support this mission, currENT has launched an effort to promote standardised modelling for innovative grid technologies, in order to ensure that best practices or standardized generic models are available to interested entities to correctly represent these innovative grid technologies. This report focuses on the modelling of SSSC and high-capacity superconductor DC cable technologies as provided by currENT member companies Smart Wires and SuperNode respectively. currENT is convinced that by enabling the modelling of these technologies, organisations that plan and operate the power system will be encouraged to study the impact of these technologies and to have more alternative approaches when innovating the power system.

The main findings and recommendations can be summarised as follows:

1. Modelling of SSSC and its controls is generally not supported by power system simulation applications and data exchange standards such as IEC 61970-600-1:2021 and IEC 61970-600-2, known as CGMES.
2. Modelling of high-capacity superconductor DC cables is supported by above mentioned data exchange standards, however guidance must be given on how to represent the technology in the study models.
3. This effort is considered to be the first real implementation of the new approach of detailed model representation defined by IEC 61970-457 standard. It has been concluded that the standard has some modelling gaps, which shall be covered in the next edition of the standard.

Recommendations:

1. Amend IEC standards and ENTSO-E specifications to include generic models of SSSC covering power flow calculations and RMS studies. This report provides necessary information to enable standardisation efforts related to IEC Common Grid Model Data Exchange Standard (CGMES) and IEC 61970-457.
2. Maintain standardised generic models as open-source code components.
3. Consider these technologies in planning for example in the ENTSO-E TYNDP project, enable planning methodologies to use innovative technologies and give guidance to scenario development.
4. Consider studies on control interaction and define approaches to optimise control settings when planning operationally to increase benefits, i.e., utilising the grid in a better way.

Furthermore, currENT would also like to acknowledge with much appreciation the crucial role of SmartWires and SuperNode that supported the work on this report and gave the permission to use all the necessary materials as well as gridDigIt that coordinated the project, performed the analysis, prepared the recommendations and the report. currENT would also like to thank TransnetBW GmbH that supported the work on the development of the generic model for SSSCs.

Introduction

Innovative grid technologies, such as those described in this report, are often not accounted for in models that form the basis for studies related to operational planning and system development, such as ENTSO-E's Ten-Year Network Development Plan (TYNDP). Studies performed by TSOs range from steady state/static analyses to dynamic analyses, i.e., a Root Mean Square (RMS) simulation or an Electromagnetic Transient (EMT) simulation. The limited modelling of innovative grid technologies in different power system analysis applications prevents TSOs and any other entities from testing the applicability of these devices or the effect of their control functions while performing system development or connection studies.

In short, having generic models which adequately represent the innovative grid technologies described in this report will enable:

1) the consideration of these technologies in planning standards and data exchange standards.
2) capability to integrate these technologies into European-wide (or other regional) dynamic models.
3) help utilities to validate vendors' proposals in their detailed planning models.
4) help vendors to demonstrate and promote their products.

In the interest of its members and to support modelling and standardisation activities worldwide, currENT has proactively launched an effort to develop generic models of innovative technologies. The objectives of the effort are as follows:

- Develop harmonised and generic models (both for static and dynamic studies) for selected number of technologies (e.g. technologies provided by Smart Wires and SuperNode).
- Promote the models for standardisation and recognition by ENTSO-E and other organisations, i.e., IEC.

currENT considers that the TYNDP mandate requires studies to provide an optimal planning, taking into account innovative technologies and methods to plan the grid while achieving socio-economic benefits. TSOs need access to the models adequately representing the behaviour of a variety of technologies to be able to incorporate significant innovation in their studies and to give them more alternatives. Without this, the TYNDP cannot consider different technology opportunities in planning the grid, in the short, medium and long term.

Models developed in this effort are suitable for power flow and RMS studies for both operational planning and system development activities. Many utilities around the world are using some of the technologies described in this study and need adequate generic models which are free from confidentiality constraints. This is especially valid for processes like the European Coordinated Security Assessment (CSA) process where the controls of the innovative technologies would play significant role in optimising necessary remedial actions. Without proper modelling, the optimisation functions might not be able to maximise the benefits of these technologies which has an adverse effect on the socio-economic impact.

This technical report describes the first set of technologies that were chosen as flagships and for which models and their machine-readable representation was prepared.

currENT recommends ENTSO-E and IEC to consider this report and promote its findings to the standardisation efforts and to utilise these models in their studies. The recognition by European TSOs and ENTSO-E of models that include the innovative grid technologies described in this report as fit for purpose for their analyses will equip TSOs worldwide with peer-reviewed generic models. Promoting these generic models to standardisation bodies will enable models to be included into industry standard proprietary power system analysis software. currENT encourages vendors of powers system analysis software to get familiar with the content and start implementing these models to enable users to utilize them in studies.

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Source code of SSSC generic model was originally developed by TransnetBW and Smart Wires and later adapted for the purpose of included in standard specifications. For additional details on the model please refer to the paper “Development of a Generic SSSC Model in PowerFactory. Convergence between IT and OT practices, Frey Florez, Santiago Mesa, 21st Wind & Solar Integration Workshop, The Hague, 12-14 October 2022.”

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Brief description of technologies in scope

Static Synchronous Series Compensator

Static synchronous series compensator (SSSC) is a power electronics flexible AC transmission system (FACTS) device that employs a voltage source converter (VSC) connected in series to a transmission line through a transformer or multilevel inverters[1].

In general, two types of SSSC devices can be distinguished:

- conventional SSSC, connected to the transmission line through a transformer;
- transformerless SSSC, connected to the transmission line through multilevel inverters.

SmartValve™ by Smart Wires is an innovative, digital, single-phase SSSC technology which belongs to the transformerless type of SSSCs. It is based on modular multilevel converter topology of serially connected low-voltage cells[2]. This SSSC can be inserted into high-voltage grid and operate at line potential without connection to the ground as a flexible line reactor or capacitor, injecting a leading or lagging voltage in quadrature with the line current and providing the functionality of a series capacitor or series reactor, respectively[3].

SSSC Principle of Operation

The operation of SSSC, whose functional diagram is given in Figure 1, is based on the principle of controlling the reactive power component of a transmission line, i.e., effective line impedance, by injecting a voltage with varying amplitude and phase. Generation of the additional voltage in the line results in an increase of the shift angle between transmitting and receiving system, and as consequence, in a decrease value of the line transfer power limit. In contrast, when a part of the voltage drop is compensated, the power transfer limit increases due to decline of the angle value. Thus, the effect of power flows redistribution and transmission line optimal loading (up to the thermal current limit) is illustrated. Thus, the device effectively imitates a serially connected inductor when voltage has leading 90∘ with grid current, and a serial capacitance when voltage has lagging 90∘ with grid current.

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[1] https://www.entsoe.eu/Technopedia/techsheets/static-synchronous-series-compensator

[2] https://www.smartwires.com/smartvalve/

[3] G. Drewry, J. Herman, B. Green, S. McGuiness and A. D. Rosso, *Evaluation of SmartValve™ Devices Installation at Central Hudson*, 2020.

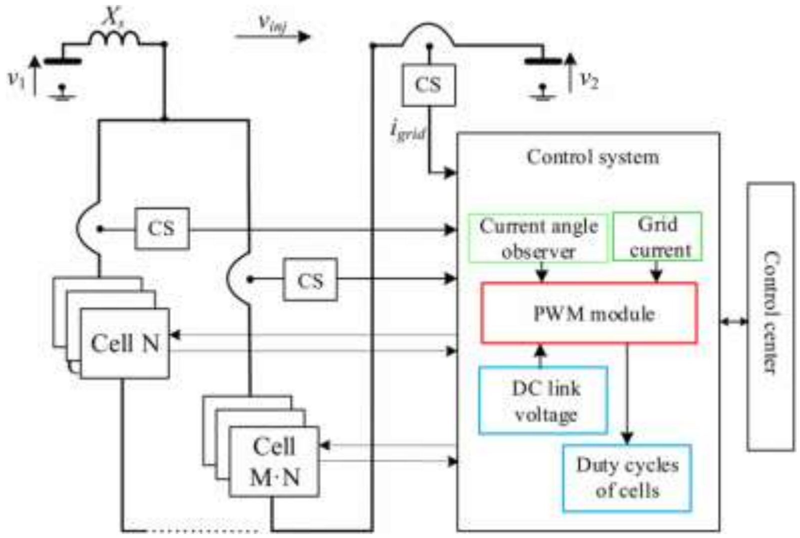

Figure 1. Functional diagram of TS-SSSC

(CS-current sensor, v1, v2-voltage of power systems, XS-line impedance, i_{grid}-grid current, v_{inj}-injection voltage)[4].

There are four different device control modes:

- Monitoring mode:
  The device bypasses, which leads to a voltage injection close to zero.
- Voltage mode:
  The device injects a fixed voltage that is either inductive or capacitive according to the specified "Voltage Set Point". The effective reactance varies according to the flow of the line current.
- Reactance mode:
  The device injects a voltage proportional to the line current to achieve the specified "Reactance Set Point". The voltage will vary according to the line current level.
- Current-control mode:
  When the current exceeds a pre-configured threshold ("Inductive Entry Threshold for Current-Control Mode") the device transitions to a latched state and injects a voltage proportional to the difference between the line current and the pre-configured current threshold.
  When the current is lower than a pre-configured threshold ("Capacitive Entry Threshold for Current-Control Mode") the device transitions to a latched state and injects a capacitive voltage that depends on the "Droop behaviour for capacitive Current-Control" as follows:
    - Disabled: the device injects its maximum capacitive voltage
    - Enabled: the device injects a capacitive voltage proportional to the difference between the line current and the Capacitive Entry Threshold

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[4] Y. Kazemirova, D. Aliamkin, N. Balashenko, A. Burmistrov, A. Zharkov and A. Anuchin, "Walking Cell Pulse-Width Modulation Strategy for a Transformerless Static Synchronous Series Compensator," 2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 2021, pp. 1-5, doi: 10.1109/RTUCON53541.2021.9711737

Additionally, the current-control override mode executes the following transitions when the current exceeds a pre-configured threshold (“Entry Threshold for Current-Control Mode”):

- When injecting an inductive voltage or in monitoring mode: the device injects a voltage proportional to the difference between the line current and the threshold.
- When injecting a capacitive voltage: the device transitions to monitoring mode.
- If the proportional voltage is lower than the initial one, the voltage injection remains unchanged.

The voltage and effective reactance of the device depend on the current according to Figure 2, which illustrates the device’s typical operating region:

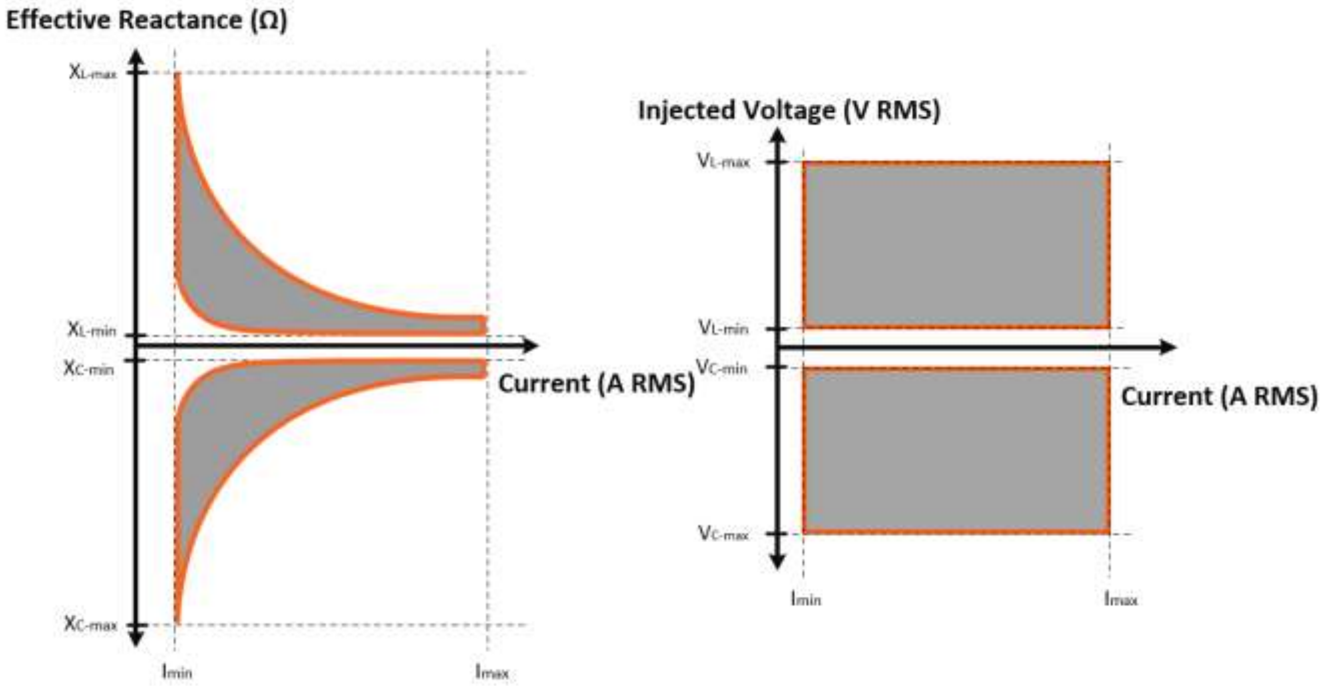

Figure 2. SSSC Operating region.

SSSC Main Features

As a transformerless, modular VSC-based alternative to the first and second generations of FACTS devices, SSSC offers numerous benefits in various network applications due to their functional and structural features, which are summarized below:

- Easiness and high speed of delivery and deployment
- Ability to offer flexible and scalable installations due to its modular design
- Possibility of both temporary, mobile and permanent solutions

- Versatility of network applications, including power flow control, as well as dynamic services
- High reliability and redundancy
- Low SSR risk of the SV compared to its Fixed Series (FSC) Capacitor counterpart
- Availability of multiple control modes
- Being voltage agnostic
- Integrated fast-acting bypass

There has been a substantial amount of research and development aimed at analysing the potential impacts of SSSC devices, focusing on its future applicability and controllability, as well as studying the response in the dynamic domain.

The most common application of SSSC is in increasing the available transfer capacity of transmission lines. The simulation study by Kreikebaum et al.[5] focused on a mobile solution (MSSSC) and discovered that the MSSSC technology can significantly increase the available transfer capacity of the existing transmission line. Moreover, it was indicated that the mobile MSSSC solution can be flexibly redeployed, fast installed, and transported. The authors have proven that the aforementioned features allow TSOs to resolve short-term system needs in multiple locations with low costs by using the limited number of devices.

By augmenting power system planning tools, it was found that the MSSSC solution has positive impacts on the day-ahead market and capital costs with given assumptions - Kreikebaum, F.; Wang, A.; Broad, S. Integration of Series FACTS into Interconnect-scale Production Cost and Long-term Planning Tools. In Proceedings of the CIGRE, Paris, Franc, 22–26 August 2016.

A 2020 technical report made by Electric Power Research Institute has shown that the flexible controllability of the SSSC enables the mobile solution to support post-contingency recoveries with advanced communication devices[6]. Therefore, SSSC can be successfully utilized to provide dynamic services. Moreover, Tupitsina[7] has shown that SSSC performs an effective influence on vibration damping in the power system at low disturbances for both operation modes.

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[5] Kreikebaum, F.; Das, D.; Yang, Y.; Lambert, F.; Divan, D. *Smart Wires—A distributed, low-cost solution for controlling power flows and monitoring transmission lines*. In Proceedings of the 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe), Gothenburg, Sweden, 11–13 October 2010.

[6] Del Rosso, A.; Drewry, G.; Herman, J.; Green, B.; McGuiness, S. Evaluation of SmartValve^{TM} Devices Installation at Central Hudson; Technical Report; Electric Power Research Institute (EPRI): Washington, DC, USA, 2020.

[7] https://urn.fi/URN:NBN:fi-fe2020052038488

A structured methodology based on frequency scanning that assesses the implications of connecting an M-FACTS device in series to a transmission line[8] has demonstrated that SmartValve will not increase the risk of undamped SSOs inflicted by SSR for networks that are stable prior to its installation.

Furthermore, a study by Abido has shown that the SSSC technology application can effectively enhance the grid stability and reliability by dynamically balancing the power flows[9].

SSSC technology can be considered as a potential solution for potential voltage control, transition stability, harmonic issues[10], and demand uncertainty management[11]

A security-constrained DCOPF-based optimisation tool to investigate the optimal allocation of the mobile MSSSC solution in transmission networks[12] discovered that the optimally allocated deployment of mobile MSSSC can effectively reduce the RES curtailment, CO_2 emissions, system generation cost, and system total cost. It has also shown positive impacts on the existing asset utilisation improvement.

Another recently analysed functionality is the provision of MTD[13]. By proactively perturbing the branch reactance, SmartValve is effective in providing Moving Target Defense (MTD), a new technology to defend against the false data injection attack (FDIA) on distribution system state estimation (DSSE), while ensuring voltage stability by minimizing the induced voltage variation.

A DNV study from 2016 conducted an economic assessment of Smart Wires' power flow control technology for improving transmission capacity on existing high voltage transmission lines in the PJM market. The study was based on a detailed transmission model for the PJM system for 2026, with scenarios involving 30% onshore wind penetration. The research first estimated the level of transmission congestion, then the optimal transmission enhancement portfolio was determined, and the identified transmission enhancements were included in a detailed nodal power flow analysis. 2 scenarios were analysed: conventional transmission enhancements and the scenario which includes conventional enhancements in addition to Smart Wires. Results show that if Smart Wires is considered as an option in

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[8] D. Zografos, C. Marmaras and F. M. Mele, "SSR Implication Assessment Using Modular FACTS," 2022 2nd International Conference on Energy Transition in the Mediterranean Area (SyNERGY MED), 2022, pp. 1-6, doi: 10.1109/SyNERGYMED55767.2022.9941389.

[9] Abido, M. Power system stability enhancement using FACTS controllers: A review. Arab. J. Sci. Eng. 2009, 34, 153–172

[10] Soroudi, A. Controllable transmission networks under demand uncertainty with modular FACTS. Int. J. Electr. Power Energy Syst. 2021, 130, 106978

[11] Fenlon, R.; Norton, M. Planning of An Efficient Power System with The Use of Modular Static Synchronous Series Compensation to Enable Flexible Operational Services. In Proceedings of the CIRED 2020 Berlin Workshop (CIRED 2020), Online, 22–23 September 2020; pp. 270–273.

[12] Zhao, Z.; Soroudi, A. *Optimal Deployment of Mobile MSSSC in Transmission System*. Energies 2022, 15, 3878. https://doi.org/10.3390/en15113878

[13] M. Liu, C. Zhao, Z. Zhang, R. Deng and P. Cheng, "Analysis of Moving Target Defense in Unbalanced and Multiphase Distribution Systems Considering Voltage Stability," 2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)

addition to conventional transmission enhancements, transmission cost savings of nearly 50% are possible while at the same time providing equal or better operational performance of the transmission system in terms of power prices, deliverability of renewable energy, transmission congestion and system costs.[14].

Applications and Best Practices

Due to its superb features summarized in the previous section, SSSC is undoubtedly a prominent technology with various possible applications. As a proof of its potential, SSSC was recognized in 2020 by the World Economic Forum within the Critical Infrastructure category as one of the top three technologies playing a fundamental role in the energy transition of the last decade[15].

The technology has been successfully demonstrated in Flexitranstore[16] projects as part of the European Commission's Horizon 2020 programme In the FLEXITRANSTORE project, which is a European Commission funded innovation project. Dramatically increased local RES integration and the availability of cross-border power flow transfer capacity. As a modular and scalable solution, SSSC enables utilities to pinpoint power demand and move energy sources where needed for efficient balance of power delivery from the transmission grid. The project confirmed that the SSSC can unlock gigawatts of new capacity on the existing grid by intelligently routing power to underutilized power lines.

In a joint project with a German TSO, Amprion, Smart Wires[17] has successfully completed a pilot test on the use of innovative technology for optimisation of grid loading. After extensive studies and technical analyses of the modular static synchronous series compensator (m-SSSC), the project concluded that SSSC can optimally utilise the capacity of the lines through targeted power flow changes (increase or decreasing power flows on a circuit). Moreover, the transmission grid can be controlled in a better way and minimise the expensive use of power plants in congestion management. Due to the technology being modular and easy to transport, it could be used in more flexible way at different locations. The new technology can thus complement conventional large and phase-shifting transformers (PST) and introduces new use cases and applications. The modular nature of the technology means that new SSC can be added to existing projects, and installed SSSC can be moved between sites depending on the capability required on each circuit at any point in time.

High-Capacity Superconductor DC Cables

A High Temperature Superconducting (HTS) power cable is a wire-based device that carries large amounts of electrical current. These conductors are placed in a pipe with vacuum (cryogen) which thermally

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[14] Computing Technologies for Smart Grids (SmartGridComm), 2021, pp. 207-213, doi: 10.1109/SmartGridComm51999.2021.963232

[15] https://www.weforum.org/whitepapers/global-innovations-from-the-energy-sector

[16] INEA. Flexitranstore. Available online: https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/grids-storage/flexitrans

[17] https://www.smartwires.com/2022/02/07/amprion-smart-wires-successfully-tested-mpfc/

isolates the superconductor from the remaining environment. They carry five times the current of a conventional cable system with the same outer dimensions, and they do not emit any heat to the environment.[18]

Principle of Operation

The basic functional principle behind SuperNode's technology is that of superconductivity[19], defined as the property of certain materials to conduct direct current (DC) electricity without energy loss when they are cooled below a critical temperature. Additional equipment is required in superconducting cable systems to keep the superconductor in the required temperature range. This is usually achieved by submerging the superconductor in a cryogenic fluid, such as liquid nitrogen, indicated in the figure below. The technology requires specific cable termination units to manage the transition to normal temperatures.

Figure 3. Structure of an HTS DC cable.

Main Features

HTS DC cables possess numerous advantages and can be successfully utilized in various power system applications. This section summarises the most important features together with references from the literature and practical applications.

- Significantly lower lifecycle costs

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[18] https://www.entsoe.eu/Technopedia/techsheets/high-temperature-superconductor-hts-cables

[19] https://supernode.energy/technology/

According to the feasibility study of Medium Voltage Direct Current (MVDC) technology with High Temperature Superconductor (HTS) cables for offshore wind power transmission[20] conducted by The University of Strathclyde, the Offshore Renewable Energy (ORE) Catapult, and SuperNode, MVDC transmission cables based on superconductors have significantly lower lifecycle costs than conventional grid technology based on High Voltage Direct Current technology in each of three analysed cost categories: costs due to electrical losses, unavailability costs and overall capital costs.

- High Power carrying capacity

Achieving higher levels of current density means that operational voltages can be reduced while still facilitating bulk power transfer at high capacities. Lower operating voltages reduce the size and volume of the electrical equipment required at both ends of the cable. This feature was verified in a feasibility study of an offshore wind farm (OWF) HVDC integration system by Xiang et al.[21] , where performance of high-temperature superconductor (HTS) DC cables (by SuperNode) under fast DC fault transients was assessed in a ±100kV/2GW point-to-point HVDC-HTS system including offshore wind farm, HTS DC cables and two converter stations using 3 parallel modular multilevel converters (MMCs). The research has proven that the second-generation HTS DC cables have the merits of a very high current capacity, smaller overall size, and higher efficiency.

- Low impact on the environment

Reaching much higher levels of current density, enabling compactness and higher capacity power transmission over the cables than conventional cables, constitutes a key advantage for the operators and the environment. A superconductor system also has a smaller footprint in an underground installation as a result of not requiring large separation between cables. The reduction in footprint for infrastructure is particularly evident for offshore applications in comparison to competing technologies.

- Inherent capacity redundancy

HTS cables can carry multiples of spare transmission capacity at little additional capital cost and no operational cost impact. This feature makes HTS cables ideally suited to meshed grid architectures in which such capacity redundancy on each link enables seamless re-routing and can be leveraged to maximise system availability. A great example of this feature is the AmpaCity project[22], a part of which

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[20] https://supernode.energy/uncategorised/supernode-superconductor-cable-shown-by-university-of-strathclyde-ore-catapult-to-be-competitive-with-hvdc/

[21] W. Xiang, W. Yuan, L. Xu, E. Hodge, J. Fitzgerald and P. McKeever, "Fault Transient Study of a Meshed DC Grid With High-Temperature Superconducting DC Cables," in IEEE Transactions on Power Delivery, vol. 37, no. 6, pp. 5414-5424, Dec. 2022, doi: 10.1109/TPWRD.2022.3177406.

[22] AmpaCity Project — World's First Superconducting Cable and Fault Current Limiter Installation in a German City Center; World Scientific Series in Applications of Superconductivity and Related Phenomena Research, Fabrication and Applications of Bi-2223 HTS Wires, pp. 263-278 (2016)

involved installing a 1 km 10 kV HTS cable in 2014 to replace a 110 kV underground cable system connecting two 10 kV substations in Essen Germany. The three-phase, concentric cable replaced the conventional 110 kV copper line connecting two substations in central Essen and eliminated the need for a high-voltage transformer at one of the substations. One of the most significant results was the cost reduction of the energy required to cool the cable down to eliminate its resistance over its lifecycle, found to be 15% lower than the equivalent cost of compensating losses in conventional 110 kV cables. Thus, HTS are one of the best technical and economically viable solutions to avoid the necessary extension of the MV/HV grid in urban areas.

Applications and Best Practices

Superconductor technologies have been utilized in a wide range of applications, some of which are outlined in the next section.

The best practice performance is illustrated for a system with parameters given below:

- Best practice performance[23]
    - HVAC: 110-220kV, 5kA
    - HVDC: 80-320kV, 10 kA
    - Impulse voltage: 1,200 kV, 60 kJ
    - Cooling temperature: -208.15°C to -193.15°C
    - Pressure: up to 2.5 MPa

- Efficient bulk power transfer:

A successful application example is the Horizon 2020 project SCARLET[24] “Superconducting cables for sustainable energy transition”, which once more proved a great applicability of superconducting cable systems solutions for more efficient bulk power transfer by carrying 500 times more electricity than copper wires and transporting up to 3.2 GW of electric power.

- Loop Applications for Reliability/Resiliency Improvement:

HTS superconductors may increase the reliability and resiliency of service to one or more substations in urban power systems. This is generally achieved by “looping” the substation together with HTS cables at the distribution voltage level such that the HTS cables behave as a “back-up” to the transmission system. This is particularly effective in case of a loss of transmission as it creates redundancy in the system, which

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[23] https://www.entsoe.eu/Technopedia/techsheets/high-temperature-superconductor-hts-cables

[24] https://cordis.europa.eu/article/id/123755-new-superconducting-cable-sets-records-for-power-transmission

was demonstrated in an EU-funded ‘Best Paths’ project by creating a new modular HVDC superconductor cable system designed for bulk power transmission over long distances with minimal resistive losses.

The Best Paths project[25] culminated with the first-ever successful qualification on a test platform of a full-scale 320 kilovolt (kV) HVDC superconducting loop. This loop comprises two terminations and a 30-meter length of cable carrying a current of 10 kiloamps (kA) for a rated power transmission capacity of 3.2 GW. The program included a complete sequence of voltage testing at 1.85 time the rated voltage (up to 592 kV) and impulse tests.

- Branch Applications for Capacity Increases:

HTS cables can also be applied to increase capacity at existing substations or serve as the primary source to new substations. Common configurations in this scenario involve distribution voltage HTS cables effectively replacing transmission voltage conventional cables as the means to move bulk power to the new or expanded substation, which eliminates the need for new transformation (and any transmission voltage equipment) at that substation.

An example of this application was laying down cables between two substations in downtown St. Petersburg spanning a distance of 2.5 km. Connecting the 330 kV ‘Tserntralnaya’[26] and 220 kV ‘RP-9’ substations will provide reserve power network capacity, allowing new consumers to connect to the system and improve system reliability and limit fault currents for existing end users.

- HPFF Cable Backup/Replacement for System Modernization:

HTS cables can be applied to assist in the transition away from High Pressure Fluid Filled (HPFF or “Pipe-Type” cables). HPFF cables technology is rapidly becoming obsolete in the unity industry primarily due to the potential environmental hazards they create (oil spills) and a single manufacturer of such cables remains active.

In addition to the past and current projects which have proven the benefits of HTS cables, a vast potential and future importance in the ever-changing power industry was recognised in a recent ENTSO-E report, ENTSO-E Vision 2050[27] - A Power System for a Carbon Neutral Europe (October 2022), in which superconductors were highlighted as one of eight potential technological and socio-economic game changers that could materialize and imply a change in the transition roadmap.

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[25] http://www.bestpaths-project.eu/

[26] V.E Sytnikov et al. HTS DC Cable Line Project: On-going Activities in Russia. IEEE Transactions on Applied Superconductivity 23, 5401904 (June 2013).

[27] https://eepublicdownloads.entsoe.eu/clean-documents/tyndp-documents/entso-_Vision_2050_report_221006.pdf

Modelling analysis and gaps

Static Synchronous Series Compensator

Unlike other network assets, the lack of available models for SSSC devices on the major simulation platforms has been identified as a market entrance barrier which has been mitigated by developing in-house device models which Smart Wires can share. For SSSC there is a need to represent the power flow controller for static studies as well as to represent controls behaviour for the need of RMS simulation. It should be noted that simulation applications such as DIgSILENT PowerFactory and Organon represent the load-flow behaviours in a useful way. The initial point of consideration is the single line diagram of a typical SSSC device, shown in the figure below:

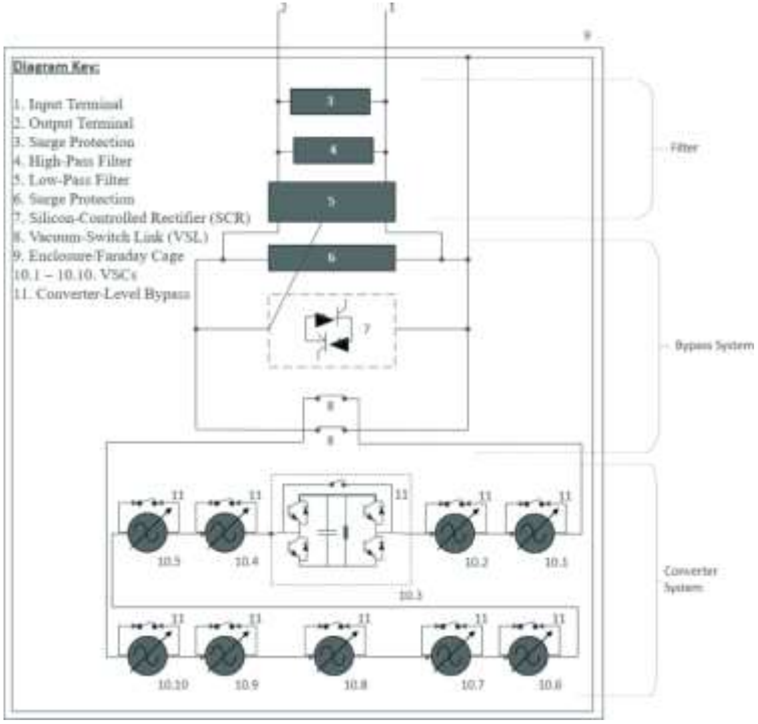

Figure 4. Single line diagram of an SSSC device.

The power flow controller has the structure as illustrated in Figure 5. Injected voltage is represented as a controllable series reactance via a series reactor. Current data exchange standards are not able to represent the SSSC and its controls for power flow studies.

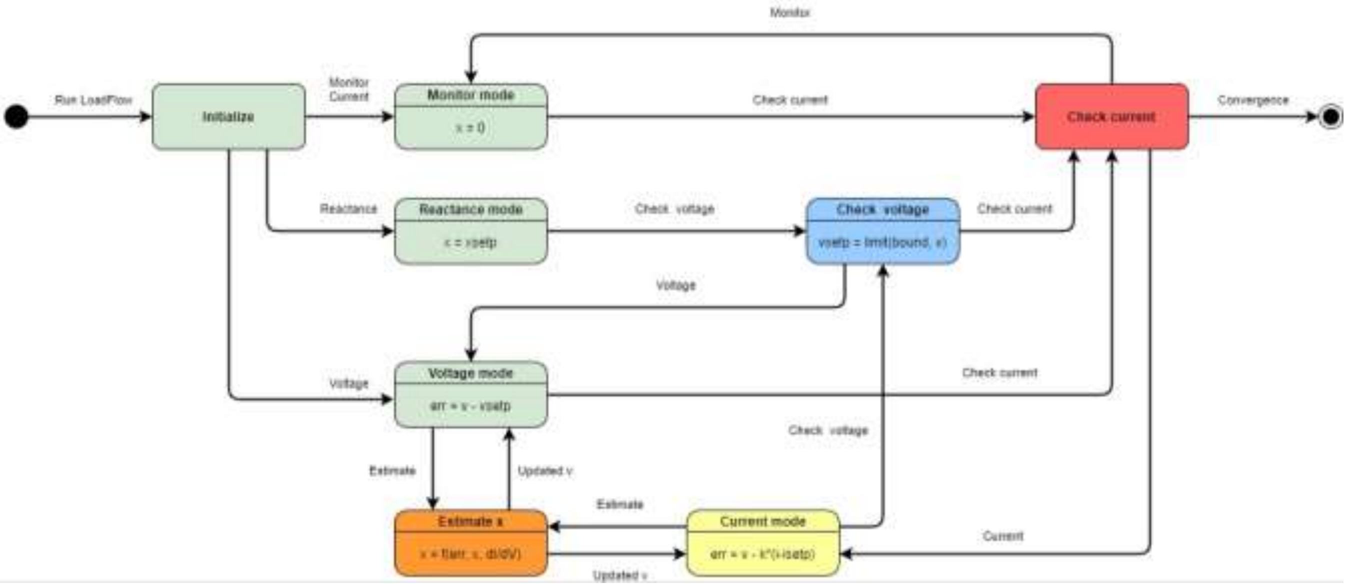

Figure 5. SSSC power flow representation.

There is a model in proprietary DIgSILENT PowerFactory format which considers the following dynamics and transitions on RMS calculations. Smart Wires has available models in PSSE, PSLF, TSAT, PSAT and Organon as well.

- Injected voltage change: Pre-defined ramp rates (in V/s) limit the changes in the injected voltage. These ramp rates can be different when increasing or decreasing the absolute voltage injection (Charging or discharging the DC link)
- Shutdown: Transitioning the device from injection to monitoring. It can be performed either in a sharp or graceful way.
- Recovery: Transitioning the device from monitoring to injection. It can be performed either in a sharp or graceful way, depending on the previous operating condition. A delay between command acknowledgment and the return to injection is considered. This delay accounts for the time required to power up the device and for the PLL to lock into the line current.
- Sharp shutdown or recovery: A step function executes the transition.
- Graceful shutdown or recovery: The transition follows the aforementioned injected voltage change dynamic.
- Polarity change: This transition considers the following sequence of events:
  - Sharp shutdown from the minimum voltage injection.
  - An intentional time delay to account for the time required to prepare the device for the change between inductive and capacitive regimes.
  - Sharp re-start to the minimum voltage injection.
- Current-mode latching: This transition considers a current threshold and an intentional delay before latching.

- Current-mode unlatching: This transition considers a current offset and an intentional delay before unlatching.
- Minimum current before returning to injection: This transition validates if the line current surpasses a given threshold before returning to injection.

In addition, the model supports the following protection functions:

- External bypass command: A sharp shutdown is executed when a positive value (e.g., 1) is received by the external bypass input.
- Overcurrent: A sharp shutdown is executed when the line current is above an over-current threshold during a given time delay.
- Time definite over-load: A graceful shutdown is executed when the line current is above the maximum emergency current during a given time delay.
- Heating over-load: A graceful shutdown is executed when the line current is above the nominal current during a given time delay.
- Low current: A sharp shutdown is executed when the line current is below the current threshold for staying in injection mode during a given time delay.
- Low Overcurrent Ride-through: A sharp shutdown is executed when the line current is above the low overcurrent ride-through threshold during a given time delay.

The following features are not included in this model:

- • Unbalanced behaviours, e.g. interphase balancing and asymmetrical faults.
- • Non-RMS behaviours, e.g. harmonics, DC bus overvoltage protection, and fast dynamic studies such as SSR oscillations.

High-Capacity Superconductor DC cables

There have been numerous attempts to model the power flow features of HCS DC cables in the literature. The most commonly proposed methodology involves modelling the cable as a generic lumped pi-section HTS cable model considering both the electrical and thermal functionalities, as proposed by Xiang et al.[28].

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[28] W. Xiang, W. Yuan, L. Xu, E. Hodge, J. Fitzgerald and P. McKeever, "Fault Transient Study of a Meshed DC Grid With High-Temperature Superconducting DC Cables," in IEEE Transactions on Power Delivery, vol. 37, no. 6, pp. 5414-5424, Dec. 2022, doi: 10.1109/TPWRD.2022.3177406.

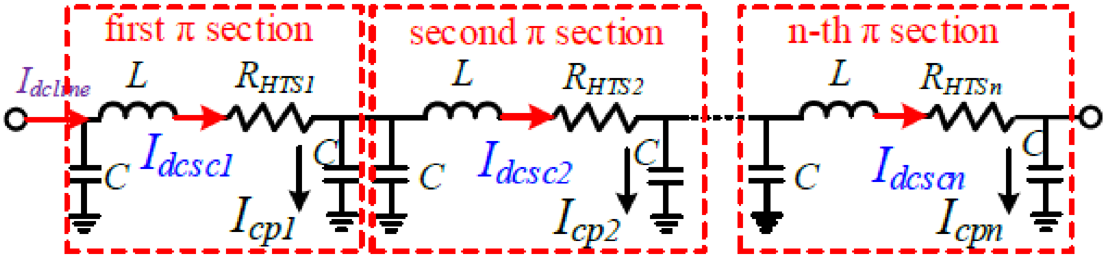

Figure 6. Lumped pi-section HTS cable model

Other proposed superconductor cable models in the literature include:

- A non-adiabatic superconductor model[29]

This model is used to simulate the thermal behaviour of a superconducting fault current limiter (SFCL) device. The model takes into account the characteristic E–J curve of the HTS material as well as the strong coupling between electrical and thermal phenomena. The one-dimensional time-dependent heat transfer across the layers of the tapes is modelled by the so called Thermal-electrical Analogy. The equivalent circuit shown below comprises a network of T sections. The thermal resistance Ri is associated with the resistance to heat flow by conduction inside the i^{th} layer, while the capacitors C_i are related to the volumetric heat capacity of the material inside the i^{th} layer. The convective heat transfer with liquid nitrogen is also represented by the thermal resistance R_{conv}. The research outlined that such a model can be employed to simulate any superconducting device based on the quench of the superconducting material just by changing geometrical and physical parameters of the limiters and materials involved.

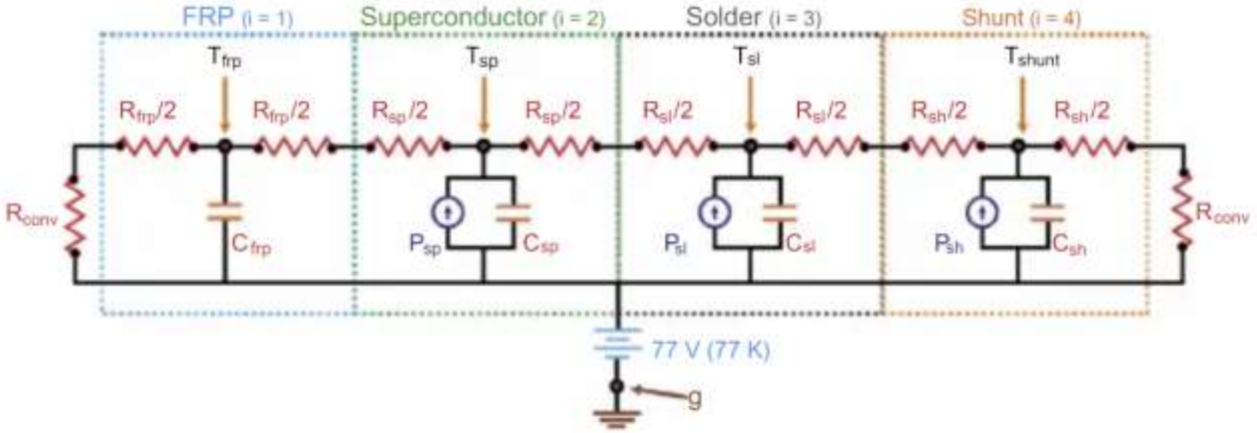

Figure 7. Thermal-electric circuit to solve the thermal behaviour of SFCL.

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[29] W.T.B. de Sousa, A. Polasek, R. Dias, C.F.T. Matt, R. de Andrade, Thermal–electrical analogy for simulations of superconducting fault current limiters, Cryogenics, Volume 62, 2014, Pages 97-109, ISSN 0011-2275, https://doi.org/10.1016/j.cryogenics.2014.04.015.

- AMSC HTC cable model[30]

In this model, the cable is represented with single, unchanging values for Inductance (reactance) and Capacitance (charging), but with two parallel branches for resistance. The resistance branches are:

1) the near zero “superconducting resistance” (Rs) and
2) the relatively large “Quenched Resistance” (Rq).

The model is operated by having all components “in-service” during the normal case. During this scenario, the value of Rs is much lower than Rq causing near zero current flowing through Rq, resulting in a near zero-resistance circuit (but still featuring Inductance and Capacitance).

When a fault is placed on the system, the switch in the Rs branch is opened (i.e., taken out of service or changing the resistance to an extremely high value), forcing all current through Rq, effectively representing the cable resistance when “quenched” or non-superconducting.

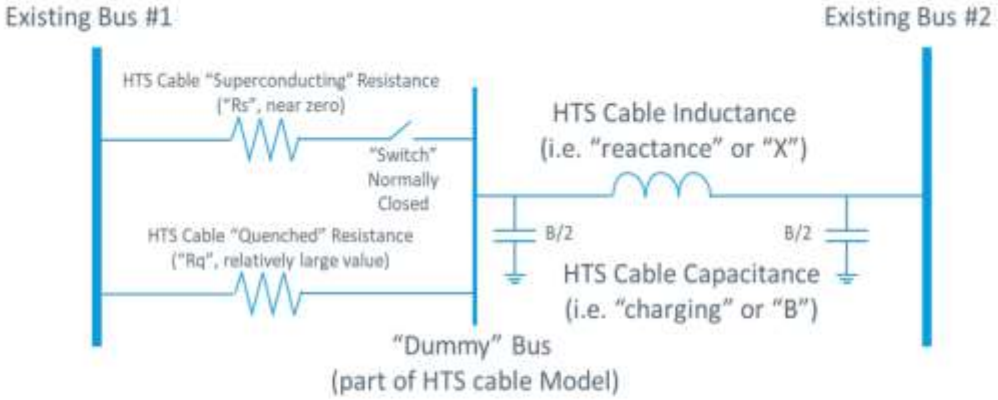

Figure 8. Equivalent circuit of AMSC HTC cable model.

Recommended modelling

Static Synchronous Series Compensator

To properly model SSSC and exchanged relevant data using CIM based approach an extended version of CGMES is needed. ENTSO-E is working on CIM/CGMES extensions to cover additional data necessary for the implementation of Network codes and Coordinated Security Assessment (CSA) methodology. The latest developments are published in the ENTSO-E web site under Apache 2 license. CurrENT used this information and based on the gap analyses proposes additional extensions, which are described in this section with more details provided in Annex A.

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[30] Application Guide for AC High Temperature Superconducting (HTS) Cables, AMSC, 2020, https://www.amsc.com/wp-content/uploads/Application-Guide-for-Superconductor-Cables-19FEB2020.pdf

The objective is to support SSSC modelling in the CGMES based data exchanges. In cases where other formats such as UCTE DEF as used, it is strongly recommended to transition to CGMES due to the following reasons:

- the conversion of SSSC model is nearly impossible as in UCTE DEF there are no controls. A converter may change impedances on interconnection, but there is no straight forward solution for this.
- The UCTE DEF support only limited number of equipment types and none of these could cover SSSC functionalities.

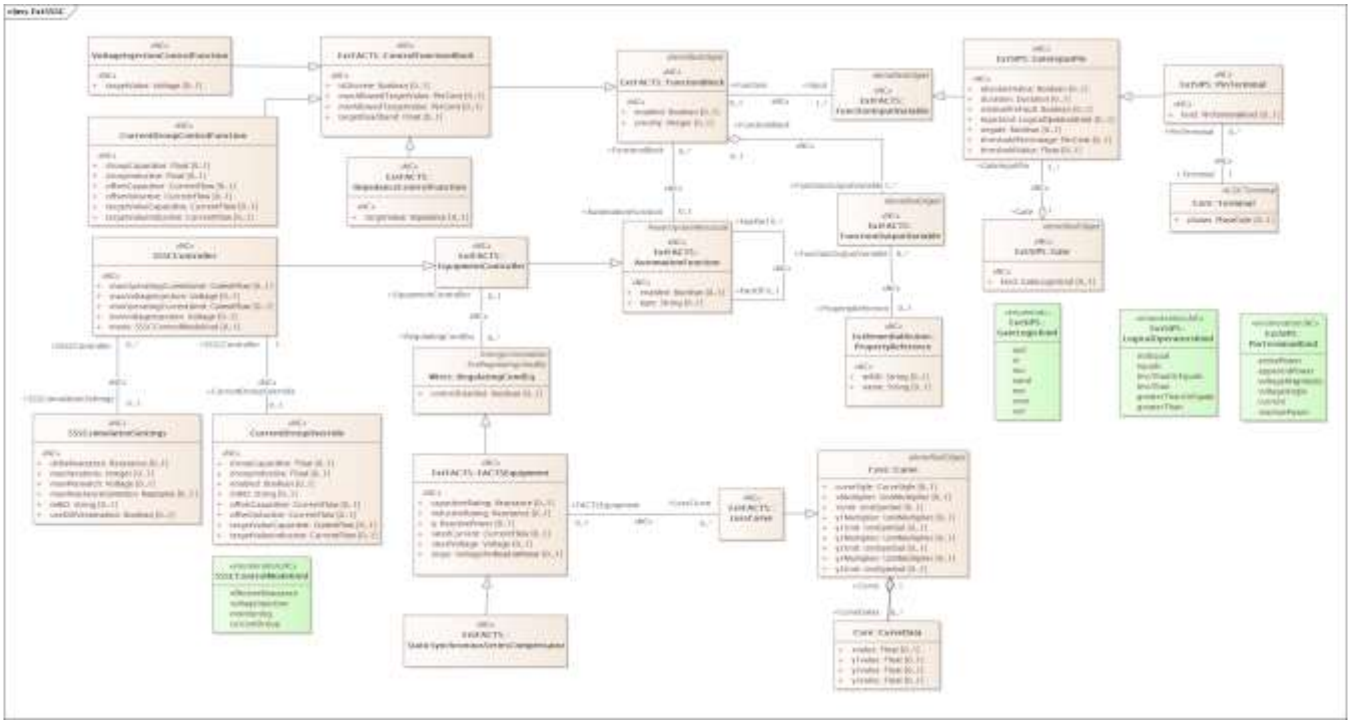

Figure 9. CIM Extensions to model controls of SSSC controller.

Figure 9 shows the proposed extensions of CIM to model SSSC and its controls for power flow calculations. The following classes and their related attributes had to be extended (Note NC namespace is used to facilitate the integration with future releases by ENTSO-E):

- SSSCController
- SSSCsimulationSettings
- VoltageInjectionControlFunction
- CurrentDroopControlFuntion
- CurrentDroopOverride
- SSSCControlModeKind

The following specifications have to be defined in the CGMES related standards:

- Information about the equipment should be provided in Equipment or EquipmentReliability profiles. This includes rated voltage and rated current information. Target values and other control related information shall be included in the profiles describing the operational scenario i.e., either Steady State Hypothesis or Steady State Instructions profiles.
- It shall be specified that SSSC is a two Terminal CIM ConductingEquipment device. It is recommended to add the following statement to the description of the StaticSynchronousSeriesCompensator: “It shall have two Terminal-s associated with it.”
- Control mode “voltage injection” is realised by using SSSCController with mode voltageInjection and a VoltageInjectionControlFunction that provides the targetValue for the control.
- The specified target voltage in case of voltage control is the target voltage injection to the terminal of the SSSC. In the data exchange it should be specified that the reference is the terminal with sequenceNumber =1.
- Control mode “effective reactance” is realised by using SSSCController with mode effectiveReactance and a ImpedanceControlFunction that provides the targetValue for the control.
- Control mode “current droop” is realised by using SSSCController with mode currentDroop and a CurrentDroopControlFuntion that provides the targetValue for the control.
- Monitoring mode observers the current and it is realised by using SSSCController with mode monitoring.
- The current droop override applies to effective reactance and voltage injection modes.

To model SSSC for RMS simulation the model should be exchanged using IEC 61970-457:Ed2 which is already approved and it is in publication process. The overall structure of the model is presented in Figure 10

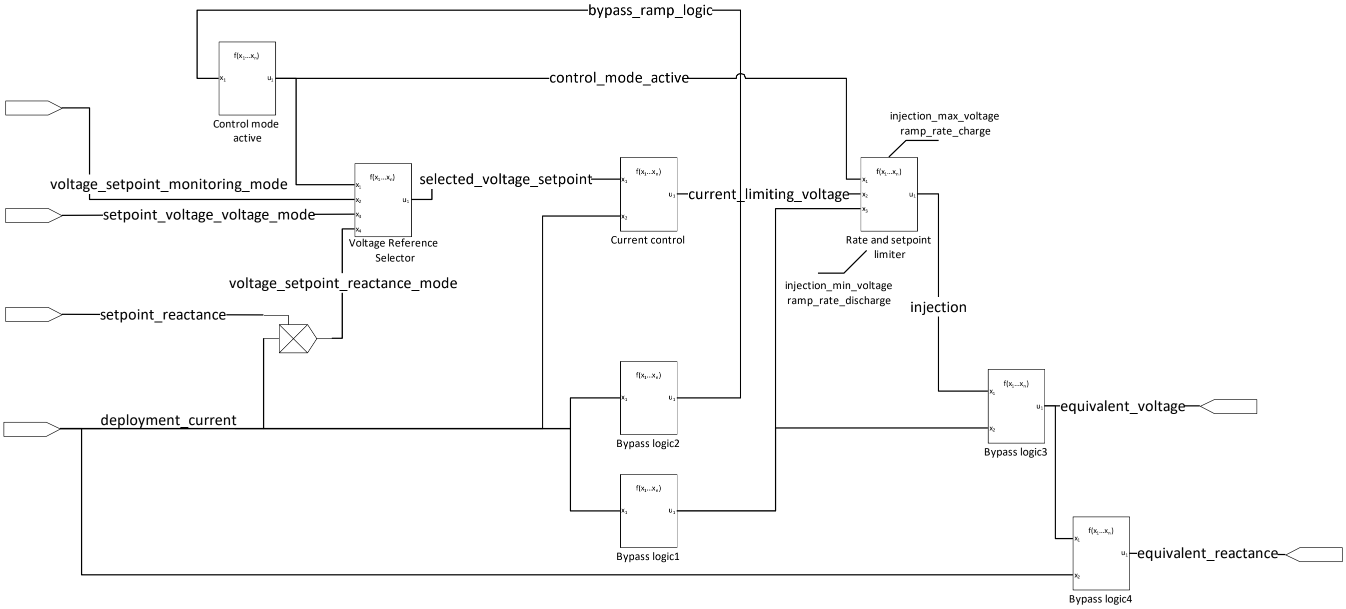

Figure 10. Structure of the RMS model of a SSSC controller.

In order to model SSSC using IEC 6197-457, the following setup is used:

- The class DetailedModelTypeDynamics is used to gather all elements of the generic model.
- There is one ParameterDescriptor per parameter of the RMS model.
- Each ParameterDescriptor is associated with a FunctionDescriptor.
- Each FunctionDescriptor is representing a function block from the diagram in Figure 10.
- One OperatorDescriptor is used to represent the multiplier.
- Input and output signals are described by SignalDescriptor.
- DetailedModelDescriptorArtifact can be used to refer directly to the json with RMS model.
- Equations are described using Modelica language syntax. It is not meant that the code is Modelica executable. This is considered as a next step.

During the modelling of the SSSC using the detailed model representation in the IEC 6197-457, the following gaps were found in the standard. It is recommended that the changes are applied in the next edition of the standard:

- The association SignalDescriptor.ACDCTerminal cannot be in the Detailed Model Configuration (DMC) profile as the configuration of the model has to be independent from the power system model to which should be applied to. This association will need to be modelled in the Detailed Model Parameterisation (DMP) Profile. As the association is optional the profile shall state that the input and output signals that are external to the model configuration shall take signals from the terminals of the device if there is no further specification.

- The attribute DetailedModelDescriptorArtifact.equationLanguageKind is required and it should be optional or the enumeration needs to include enum "other".
- The enumeration XSDDatatypeKind is missing integer enumerated value.
- There is a typo on the class name ParameterDesctiptor. It should be ParameterDescriptor.
- The association between ParameterDescriptor and FunctionDescriptor has multiplicities 1..* and 1 and direction towards FunctionDescriptor. This requires that each FunctionDesctiptor shall have a parameter and each parameter shall point to a FunctionDescriptor. It is recommended that the association is left with multiplicities 0..* and 0..* with direction towards ParameterDescriptor. This would allow the following:
  - To model a FunctionDescriptor without parameters
  - To reuse parameters in different FunctionDescriptor-s
  - To list all parameters for a FunctionDescriptor.
- The InputOutputDescriptor is allowed to have multiple inputs but only one output. It is recommended to change the multiplicity of InputOutputDescriptor.SignalDescriptor to 1..*. This will allow modelling complex functions with multiple outputs.

High-Capacity Superconductor DC cables

As summarised in previous sections, the main features of SuperNode cables, from the power system modelling point of view are:

- High power density (i.e. small cross-sectional area)
- Thermal isolation (no heat emitted from cables)
- Nearly undetectable Electro-Magnet Fields (near zero EMF)

The key consideration with the modelling of HTS cables is capturing the change in impedance of the cable during fault conditions (i.e., the Fault Current Limiting feature). This characteristic is a fundamental difference between HTS cables and conventional copper or aluminium cables.

Considering that the power flow representation of HTC cables is the focus of this report, as a model which accurately captures the previous notions, the lumped pi model of HTS cable, is adopted in this report by taking the cable resistance, inductance and capacitance into consideration.

Another important consideration is the ability to represent the different segments' electrical parameters. For this purpose, the IEC Common Information Model-based DCLineModel, illustrated in the figure below, was assessed to find any deficiencies in current modelling. It was found out that no modifications of the current standard are necessary. Therefore, it can be concluded that the model below is sufficient for power flow studies without additional extensions, since additional parameters and restrictions such as making attributes mandatory or restricting the cardinalities on associations are not found to be necessary.

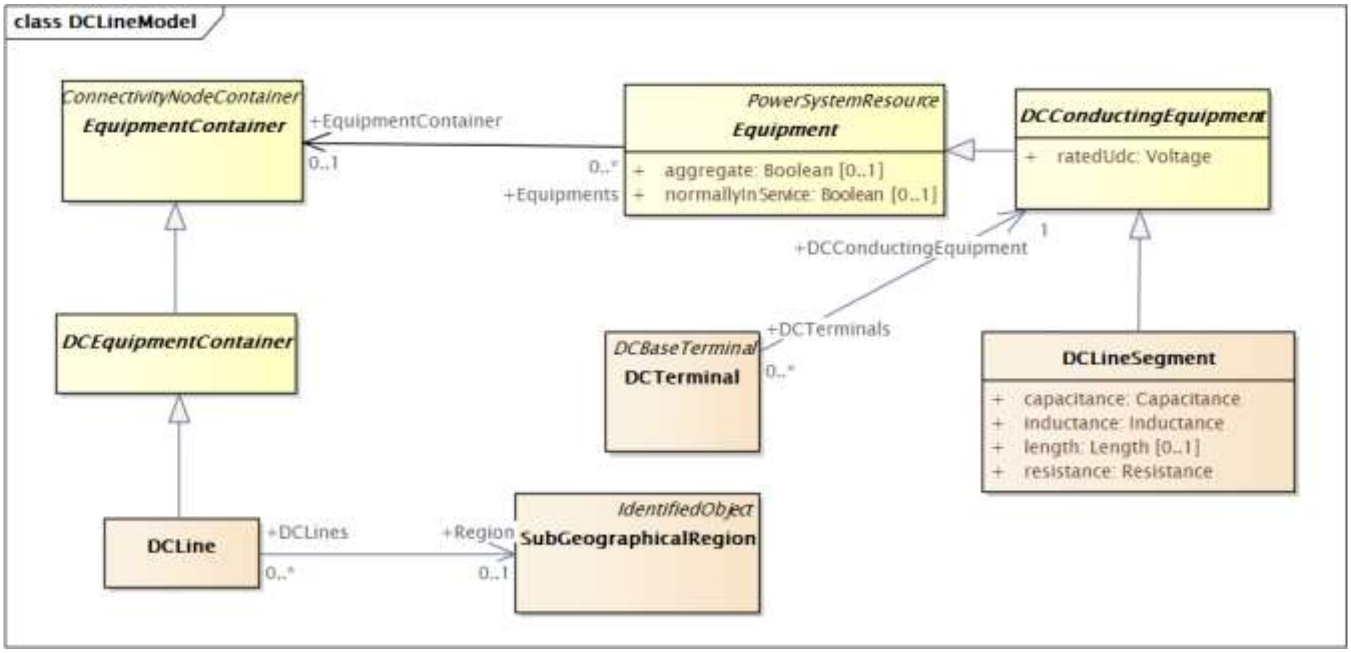

Figure 11. CIM model of a DC line.

Annex A: Proposed models

Model A: CIM based model of Static Synchronous Series Compensator

The following sections provide details on the CIM extensions needed to adequately represent SSSC for power flow calculations. The NC (Network Code) notation indicates the namespace of the extensions.

(NC) SSSCsimulationSettings

SSSC control simulation settings used by the algorithm for power flow calculations.
Table 1 shows all attributes of SSSCsimulationSettings.

Table 1 – Attributes of ExtSSSC::SSSCsimulationSettings

name	mult	type	description
maxReactanceCorrection	0..1	Reactance	(NC) Maximum value of the reactance correction applied between Iterations of the

name	mult	type	description
			power flow calculation algorithm for the purpose of achieving control target value.
maxMismatch	0..1	Voltage	(NC) Maximum mismatch tolerance of voltage target value. If mismatch is lower, convergence is claimed. It is only used for voltageInjection and currentDroop control modes.
deltaReactance	0..1	Reactance	(NC) Reactance delta for the solution algorithm. The solution “outer-loop” algorithm is based on a secant method which needs two initial points. The second point is calculated from the first one by either adding or subtracting this “delta”. The “seed” is assumed to be 0 ohms.
useDIDVestimation	0..1	Boolean	(NC) Defines if the estimate is considering the dI/dV sensitivity (true) instead of the secant algorithm (false).
maxIterations	0..1	Integer	(NC) Maximum number of iterations before claiming an open line condition. The algorithm uses it to assess if a line is really open by making sure low-currents are observed on various consecutive iterations.
mRID	0..1	String	(NC) Master resource identifier issued by a model authority. The mRID is unique within an exchange context. Global uniqueness is easily achieved by using a UUID, as specified in RFC 4122, for the mRID. The use of UUID is strongly recommended. For CIMXML data files in RDF syntax conforming to IEC 61970-552, the mRID is mapped to rdf:ID or rdf:about attributes that identify CIM object elements.

Table 2 shows all association ends of SSSCsimulationSettings with other classes.

Table 2 – Association ends of ExtSSSC::SSSCsimulationSettings with other classes

mult from	name	mult to	type	description
0..1	SSSCController	0..*	SSSCController	(NC) The controller that uses these simulation settings.

(NC) CurrentDroopControlFunction

Inheritance path = ControlFunctionBlock : FunctionBlock : IdentifiedObject : ExtEuIdentifiedObject
Current droop control function is a function block that calculates the operating point of the controlled equipment to achieve the target current.
Table 3 shows all attributes of CurrentDroopControlFunction.

Table 3 – Attributes of ExtSSSC::CurrentDroopControlFunction

name	mult	type	description
targetValueInductive	0..1	CurrentFlow	(NC) Setpoint when control is active in inductive region.
offsetInductive	0..1	CurrentFlow	(NC) Offset in capacitive region.
droopInductive	0..1	Float	(NC) Droop in inductive region. The unit is V/A.
targetValueCapacitive	0..1	CurrentFlow	(NC) Setpoint when control is active in capacitive region.
offsetCapacitive	0..1	CurrentFlow	(NC) Offset in capacitive region.
droopCapacitive	0..1	Float	(NC) Droop in capacitive region. The unit is V/A.
isDiscrete	0..1	Boolean	(NC) inherited from: ControlFunctionBlock
targetDeadband	0..1	Float	(NC) inherited from: ControlFunctionBlock
maxAllowedTargetValue	0..1	PerCent	(NC) inherited from: ControlFunctionBlock
minAllowedTargetValue	0..1	PerCent	(NC) inherited from: ControlFunctionBlock
enabled	0..1	Boolean	(NC) inherited from: FunctionBlock
priority	0..1	Integer	(NC) inherited from: FunctionBlock
aliasName	0..1	String	inherited from: IdentifiedObject
description	0..1	String	inherited from: IdentifiedObject
mRID	0..1	String	inherited from: IdentifiedObject
name	0..1	String	inherited from: IdentifiedObject
energyIdentCodeEic	0..1	String	(European) inherited from: ExtEuIdentifiedObject
shortName	0..1	String	(European) inherited from: ExtEuIdentifiedObject

Table 4 shows all association ends of CurrentDroopControlFunction with other classes.

Table 4 – Association ends of ExtSSSC::CurrentDroopControlFunction with other classes

mult from	name	mult to	type	description
1..1	ControlFunctionBlockAction	0..*	ControlFunctionBlockAction	(NC) inherited from: ControlFunctionBlock
0..*	AutomationFunction	0..1	AutomationFunction	(NC) inherited from: FunctionBlock
0..1	Input	1..*	FunctionInputVariable	(NC) inherited from: FunctionBlock
0..1	FunctionOutputVariable	1..*	FunctionOutputVariable	(NC) inherited from: FunctionBlock
0..1	DiagramObjects	0..*	DiagramObject	inherited from: IdentifiedObject
1..1	Names	0..*	Name	inherited from: IdentifiedObject
0..1	ParameterEvent	0..*	ParameterEvent	inherited from: IdentifiedObject
0..1	AlternativeIdentifier	0..*	Name	(NC) inherited from: IdentifiedObject
0..1	Name	0..*	Name	(NC) inherited from: IdentifiedObject

(NC) CurrentDroopOverride

Current droop override uses the following logic:

- When the current exceeds a threshold the device executes the following transitions: 1) When injecting an inductive voltage or in monitoring mode the device tends to inject a voltage proportional to the difference between the line current and the aforementioned threshold. 2) When injecting a capacitive voltage the device transitions to monitoring mode.
- If the aforementioned proportional voltage is lower than the initial one, the voltage injection remains unchanged.

Current droop override is not applied when the device operates in currentDroop mode.

Table 5 shows all attributes of CurrentDroopOverride.

Table 5 – Attributes of ExtSSSC::CurrentDroopOverride

name	mult	type	description
droopCapacitive	0..1	Float	(NC) Droop in capacitive region. The unit is V/A.
droopInductive	0..1	Float	(NC) Droop in inductive region. The unit is V/A.
enabled	0..1	Boolean	(NC) True, if the current droop override is enabled (active). Otherwise false.
offsetCapacitive	0..1	CurrentFlow	(NC) Offset in capacitive region.
offsetInductive	0..1	CurrentFlow	(NC) Offset in capacitive region.

name	mult	type	description
targetValueCapacitive	0..1	CurrentFlow	(NC) Setpoint when control is active in capacitive region.
targetValueInductive	0..1	CurrentFlow	(NC) Setpoint when control is active in inductive region.
mRID	0..1	String	(NC) Master resource identifier issued by a model authority. The mRID is unique within an exchange context. Global uniqueness is easily achieved by using a UUID, as specified in RFC 4122, for the mRID. The use of UUID is strongly recommended. For CIMXML data files in RDF syntax conforming to IEC 61970-552, the mRID is mapped to rdf:ID or rdf:about attributes that identify CIM object elements.

Table 6 shows all association ends of CurrentDroopOverride with other classes.

Table 6 – Association ends of ExtSSSC::CurrentDroopOverride with other classes

mult from	name	mult to	type	description
0..1	SSSCController	1..1	SSSCController	(NC) The SSSC controller to which this CurrentDroopOverride applies to.

(NC) SSSCController

Inheritance path = EquipmentController : AutomationFunction : PowerSystemResource : IdentifiedObject : ExtEuIdentifiedObject

The controller of a Static synchronous series compensator (SSSC).

Table 7 shows all attributes of SSSCController.

Table 7 – Attributes of ExtSSSC::SSSCController

name	mult	type	description
mode	0..1	SSSCControlModeKind	(NC) Mode of the Static Synchronous Series compensator controller.
minVoltageInjection	0..1	Voltage	(NC) Minimum voltage that the device can inject.
maxVoltageInjection	0..1	Voltage	(NC) Maximum voltage that the device can inject.

name	mult	type	description
maxOperatingCurrentLimit	0..1	CurrentFlow	(NC) Maximum operating current limit applied for the controller and used by any of the available control functions.
minOperatingCurrentLimit	0..1	CurrentFlow	(NC) Minimum operating current limit applied for the controller and used by any of the available control functions.
enabled	0..1	Boolean	(NC) inherited from: AutomationFunction
type	0..1	String	(NC) inherited from: AutomationFunction
aliasName	0..1	String	inherited from: IdentifiedObject
description	0..1	String	inherited from: IdentifiedObject
mRID	0..1	String	inherited from: IdentifiedObject
name	0..1	String	inherited from: IdentifiedObject
energyIdentCodeEic	0..1	String	(European) inherited from: ExtEuIdentifiedObject
shortName	0..1	String	(European) inherited from: ExtEuIdentifiedObject

Table 8 shows all association ends of SSSCController with other classes.

Table 8 – Association ends of ExtSSSC::SSSCController with other classes

mult from	name	mult to	type	description
0..*	SSSCsimulationSettings	0..1	SSSCsimulationSettings	(NC) The simulation setings that apply for this controller.
1..1	CurrentDroopOverride	0..1	CurrentDroopOverride	(NC) The current droop override for this SSSC controller. It is not used when the SSSC controller is in mode currentDroop.
0..1	RegulatingCondEq	0..*	RegulatingCondEq	(NC) inherited from: EquipmentController
0..1	HasPart	0..*	AutomationFunction	(NC) inherited from: AutomationFunction
0..1	FunctionBlock	0..*	FunctionBlock	(NC) inherited from: AutomationFunction
0..*	PartOf	0..1	AutomationFunction	(NC) inherited from: AutomationFunction
0..*	PSRType	0..1	PSRType	inherited from: PowerSystemResource

mult from	name	mult to	type	description
0..1	Controls	0..*	Control	inherited from: PowerSystemResource
0..1	Measurements	0..*	Measurement	inherited from: PowerSystemResource
1..1	OperatingShare	0..*	OperatingShare	inherited from: PowerSystemResource
0..*	ReportingGroup	0..*	ReportingGroup	inherited from: PowerSystemResource
0..1	DiagramObjects	0..*	DiagramObject	inherited from: IdentifiedObject
1..1	Names	0..*	Name	inherited from: IdentifiedObject
0..1	ParameterEvent	0..*	ParameterEvent	inherited from: IdentifiedObject
0..1	AlternativeIdentifier	0..*	Name	(NC) inherited from: IdentifiedObject
0..1	Name	0..*	Name	(NC) inherited from: IdentifiedObject

(NC) VoltageInjectionControlFunction

Inheritance path = ControlFunctionBlock : FunctionBlock : IdentifiedObject : ExtEuIdentifiedObject
Voltage injection control function is a function block that calculates the operating point of the controlled equipment to achieve the target voltage injection. The controlled point is the Terminal with sequenceNumber =1.
Table 9 shows all attributes of VoltageInjectionControlFunction.

Table 9 – Attributes of ExtSSSC::VoltageInjectionControlFunction

name	mult	type	description
targetValue	0..1	Voltage	(NC) Target value for the voltage that the control function is calculating to achieve by adjusting the operational setting to the controlled equipment.
isDiscrete	0..1	Boolean	(NC) inherited from: ControlFunctionBlock
targetDeadband	0..1	Float	(NC) inherited from: ControlFunctionBlock
maxAllowedTargetValue	0..1	PerCent	(NC) inherited from: ControlFunctionBlock
minAllowedTargetValue	0..1	PerCent	(NC) inherited from: ControlFunctionBlock
enabled	0..1	Boolean	(NC) inherited from: FunctionBlock
priority	0..1	Integer	(NC) inherited from: FunctionBlock
aliasName	0..1	String	inherited from: IdentifiedObject
description	0..1	String	inherited from: IdentifiedObject

name	mult	type	description
mRID	0..1	String	inherited from: IdentifiedObject
name	0..1	String	inherited from: IdentifiedObject
energyIdentCodeEic	0..1	String	(European) inherited from: ExtEuIdentifiedObject
shortName	0..1	String	(European) inherited from: ExtEuIdentifiedObject

Table 10 shows all association ends of VoltageInjectionControlFunction with other classes.

Table 10 – Association ends of ExtSSSC::VoltageInjectionControlFunction with other classes

mult from	name	mult to	type	description
1..1	ControlFunctionBlockAction	0..*	ControlFunctionBlockAction	(NC) inherited from: ControlFunctionBlock
0..*	AutomationFunction	0..1	AutomationFunction	(NC) inherited from: FunctionBlock
0..1	Input	1..*	FunctionInputVariable	(NC) inherited from: FunctionBlock
0..1	FunctionOutputVariable	1..*	FunctionOutputVariable	(NC) inherited from: FunctionBlock
0..1	DiagramObjects	0..*	DiagramObject	inherited from: IdentifiedObject
1..1	Names	0..*	Name	inherited from: IdentifiedObject
0..1	ParameterEvent	0..*	ParameterEvent	inherited from: IdentifiedObject
0..1	AlternativeIdentifier	0..*	Name	(NC) inherited from: IdentifiedObject
0..1	Name	0..*	Name	(NC) inherited from: IdentifiedObject

(NC) SSSCControlModeKind enumeration

Control modes of the Static Synchronous Series Compensator (SSSC).

Table 11 shows all literals of SSSCControlModeKind.

Table 11 – Literals of ExtSSSC::SSSCControlModeKind

literal	value	description
effectiveReactance		The device injects a voltage proportional to the line current to achieve the specified target value defined by the ImpedanceControlFunction. The voltage will vary according to the line current level.
voltageInjection		The device injects a fixed voltage that is either inductive or capacitive according to the specified target value of the VoltageInjectionControlFunction. The

literal	value	description
		effective reactance varies according to the flow of the line current.
monitoring		The device bypasses and a voltage injection is close to zero. In monitoring mode current is monitored.
currentDroop		The device injects a voltage proportional to the difference between the line current and the target value of the CurrentDroopControlFunction. There are capacitive and inductive operational regions.

Model B: Detailed model type dynamics of SSSC generic RMS model

The detailed modelling of SSSC generic RMS model is available in the following two files:

- SSSC_RMS_model_DMC.xml - Includes the way to exchange the configuration of the detailed model
- SSSC_RMS_model_DMP.xml – Includes the way to exchange the parameters of the detailed model