APPLICATION OF INNOVATIVE TRANSMISSION TECHNOLOGIES FOR THE DEVELOPMENT OF THE FUTURE EUROPEAN POWER SYSTEM

Angelo L'Abbate * Angelo.LAbbate@rse-web.it

Gianluca Fulli ** Gianluca.FULLI@ec.europa.eu

Gianluigi Migliavacca * Gianluigi.Migliavacca@rse-web.it

Arturs Purvins ** Arturs.PURVINS@ec.europa.eu

*: RSE (Ricerca sul Sistema Energetico)[1] SpA
Milan, Italy

**: Institute for Energy – JRC – European Commission
Petten, The Netherlands

Abstract – The present paper focuses on main technical, environmental, and economic features of three types of advanced transmission technologies, currently having a different level of maturity and deployment in Europe. The devices addressed in this paper are the SSSC (Static Synchronous Series Compensator), the VSC (Voltage Source Converter)-HVDC (High Voltage Direct Current) and the GIL (Gas Insulated Line). The aim is to investigate the application of these advanced technologies in the future European power system. Towards this purpose, steady-state modeling is an essential stage; in particular, an original SSSC model is presented and validated. Techno-economic analyses for implementing SSSC and for comparing VSC-HVDC and GIL in specific applications in the future European power system are then carried out.

Keywords: cost-benefit analysis, FACTS, GIL, HVDC, power flow analysis, SSSC, steady-state modeling, transmission planning.

1 INTRODUCTION

The electric power system in Europe is currently challenged by crucial issues concerning security of energy supply, electricity market restructuring and increasing environmental sustainability constraints. Tackling these issues may significantly impact on the design and the operation of the European electricity grids: concerning transmission infrastructures, as recently reaffirmed [1], they are on the critical path to meet the European Union's climate change and energy policy objectives for 2020 and beyond. In particular, the challenge will mostly be the integration of very large amounts of variable renewable energy sources (RES) into the power system, while keeping its security and reliability levels, in a liberalised background. To this scope, a more flexible and controllable transmission grid would be then needed. Furthermore, the ongoing energy market liberalisation process in Europe is leading to the steady rise of inter-area power exchanges, generally increasing the transmission network congestion. To address such issues, the solution of enhancing the power transmission capacity, traditionally realized by adding new High Voltage Alternating Current (HVAC) infrastructures, is nowadays seriously hampered by economic, social and environmental constraints.

Thus, the need for evolution in the design and operation of transmission networks emerges in Europe.

This will require a re-engineering process which will be supported by the utilisation of mature and innovative power transmission technologies. Among them, a crucial role may be played by advanced devices like FACTS (Flexible Alternating Current Transmission System) and HVDC (High Voltage Direct Current) technologies. These power electronics-based devices offer the possibility to increase transmission capacity and flexibility and generally enhance system reliability and controllability with a limited environmental impact. These properties are especially important in a deregulated environment, where, in presence of more frequent and severe corridor congestions, fast-reacting FACTS and HVDC elements can efficiently avoid or relieve network constraints. Moreover, the deployment of FACTS and HVDC can allow a further integration of variable RES power plants into the European power system. In this sense, particular attention is currently paid in Europe to VSC (Voltage Source Converter)-HVDC, while an advanced, fast power flow controlling device of the FACTS family like the SSSC (Static Synchronous Series Compensator) is under scrutiny for a wider deployment. Another very promising technology offering crucial benefits of transmission capacity increase and reliability system enhancement is represented by the GIL (Gas Insulated Line).

The present paper partially results from the activities ongoing within the European research project named REALISEGRID [2]. Focus is on three types of innovative transmission technologies, namely SSSC, VSC-HVDC and GIL, featuring different levels of maturity and deployment in Europe, with the second one being the most mature of the three. The aim is to investigate the application of these technologies for the development of the future European power system. Towards this scope, it is essential to model these technologies for steady-state studies. Different models of these devices are part of the paper (Section 2); in particular, an original SSSC model for load flow applications is introduced. Section 2 also recaps main technical features of the three technologies, while Section 3 and Section 4 respectively focus on main environmental and economic features of the above devices. All these elements are key aspects to support transmission planners in the crucial stage of cost-benefit

[1] Former ERSE, previously CESI RICERCA

analysis in order to select the most sound expansion alternative. Then, validation of the SSSC model as well as techno-economic analyses for implementing SSSC and for comparing VSC-HVDC and GIL technologies embedded in the synchronized European transmission grid are specifically carried out in Section 5.

2 TECHNICAL FEATURES AND MODELING

2.1 SSSC

An extensive literature is available on FACTS devices (see [13][14][15] among others). These power electronics-based transmission technologies give the possibility to fast control one or more of the interdependent network operation parameters. Among FACTS technologies, a very promising device is the SSSC, which could also be considered as the series part of the UPFC (Unified Power Flow Controller), the most powerful and versatile FACTS controller [25][26]. Different features of the SSSC have been investigated in the literature [7][8],[12]-[15]: SSSC is a fast power flow controlling device. A basic scheme of SSSC is shown in Figure 1Figure 1: .

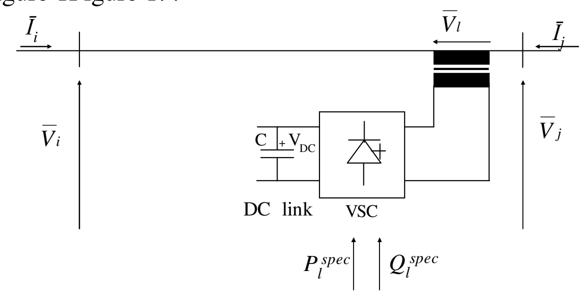

Figure 1: SSSC basic scheme.

The SSSC basically consists of a coupling transformer, a series connected voltage source converter for the smooth AC (Alternating Current) – DC (Direct Current) conversion, and a DC circuit. The injected voltage of the coupling transformer is perpendicular to the line current, like for a series capacitor or reactor. However, differently from those devices, a SSSC acts as a controllable voltage source whose voltage magnitude can be in an operating area controlled independently of the line current. The SSSC can be considered functionally as an ideal generator that can be operated with a relatively small DC storage capacitor in a self-sufficient manner to exchange reactive power with the AC system or, with an external DC power supply or energy storage, to also exchange independently controllable active power. In Figure 1 P_l^{spec}, Q_l^{spec} are the specified active and reactive power to be exchanged from the series converter at the AC output: they define the output voltage angle and magnitude generated from the series converter. In order to model the SSSC for steady-state studies the equivalent SSSC representation shown in Figure 2 has been taken into account. It leads to a SSSC model which can be referred to as Voltage Source Model (VSM) [8][11]. In the VSM representation, considering exclusively the SSSC in a line linking the nodes *i* and *j*, the equivalent SSSC circuit consists of a voltage source, $\bar{V}_l$, with the admittance, $\dot{Y}_l$, of the coupling transformer at the series converter terminal. The voltage source is assumed to be ideal; it can be then expressed as:

$$\bar{V}_l = V_l \;(\cos\vartheta_l + \mathrm{j}\sin\vartheta_l) \qquad (1)$$

where V_l, ϑ_l are the controllable magnitude and angle of the SSSC having the limits: $V_{l\ \min} \leqslant V_l \leqslant V_{l\ \max}$, $0 \leqslant \vartheta_l \leqslant 2\pi$. The coupling admittance can be formulated as:

$$\dot{Y}_l = Y_l\, e^{-\mathrm{j}\varphi l} = G_l + \mathrm{j}B_l \qquad (2)$$

where Y_l and $-\varphi_l$ respectively express the amplitude and phase of the coupling SSSC admittance, while G_l, B_l represent the coupling conductance and susceptance of the SSSC, respectively.

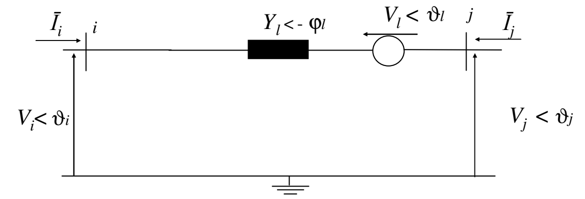

Figure 2: SSSC Voltage Source Model.

By the assumption that there are no power losses inside the SSSC converter, in absence of an external DC power source, the device globally neither produces nor absorbs active power to/from the AC system. Then, the following equality constraint has to be guaranteed (* indicates the complex conjugate component)

$$P_l = \mathrm{Re}\,\{\bar{V}_l\,\bar{I}_j^{\,*}\} = 0 \qquad (3)$$

In literature [8] it has been described how the SSSC VSM can be incorporated into existing Newton-Raphson algorithms for power flow studies. For the different SSSC control functions, under opportune initialization of the SSSC variables (voltage magnitude and angle, V_l and ϑ_l, respectively), quadratic load flow convergence can be achieved. Despite its advantages [8], the VSM introduces however some difficulties in modeling the system with embedded SSSCs due to the presence of the voltage source. In fact, in order to have a square admittance matrix, the introduction of one fictitious node is needed for each SSSC. Also, the symmetry properties of the admittance matrix are lost.

In the following, as a more robust and feasible option, a Power Injection Model (PIM) for the SSSC implementation is originally introduced and analyzed. It is derived from the VSM and offers the same advantages, but it bypasses the presence of the voltage source and the resulting admittance matrix is symmetric. From the scheme in Figure 2 and by (1), (2), the active power by the SSSC can be calculated as:

$$\begin{aligned} P_l = V_l^{\,2} G_l + V_l V_j\,[G_l\cos(\vartheta_l - \vartheta_j) + B_l\sin(\vartheta_l - \vartheta_j)] + \\ - V_l V_i\,[G_l\cos(\vartheta_l - \vartheta_i) + B_l\sin(\vartheta_l - \vartheta_i)] \end{aligned} \qquad (4)$$

Also, the load flow equations at nodes *i* and *j* can be obtained respectively as:

$$P_i = V_i^2 G_l - V_i V_j [G_l \cos(\vartheta_i - \vartheta_j) + B_l \sin(\vartheta_i - \vartheta_j)] + \\ - V_i V_l [G_l \cos(\vartheta_i - \vartheta_l) + B_l \sin(\vartheta_i - \vartheta_l)] \quad (5)$$

$$Q_i = - V_i^2 B_l - V_i V_j [G_l \sin(\vartheta_i - \vartheta_j) - B_l \cos(\vartheta_i - \vartheta_j)] + \\ - V_i V_l [G_l \sin(\vartheta_i - \vartheta_l) - B_l \cos(\vartheta_i - \vartheta_l)] \quad (6)$$

$$P_j = V_j^2 G_l - V_j V_i [G_l \cos(\vartheta_j - \vartheta_i) + B_l \sin(\vartheta_j - \vartheta_i)] + \\ + V_j V_l [G_l \cos(\vartheta_j - \vartheta_l) + B_l \sin(\vartheta_j - \vartheta_l)] \quad (7)$$

$$Q_j = - V_j^2 B_l - V_j V_i [G_l \sin(\vartheta_j - \vartheta_i) - B_l \cos(\vartheta_j - \vartheta_i)] + \\ + V_j V_l [G_l \sin(\vartheta_j - \vartheta_l) - B_l \cos(\vartheta_j - \vartheta_l)] \quad (8)$$

Focusing on (5), it can be written

$$P_i = V_i^2 G_l - V_i V_j [G_l \cos(\vartheta_i - \vartheta_j) + B_l \sin(\vartheta_i - \vartheta_j)] - P_i^{SSSC} \quad (9)$$

with

$$P_i^{SSSC} = V_i V_l [G_l \cos(\vartheta_i - \vartheta_l) + B_l \sin(\vartheta_i - \vartheta_l)] \quad (10)$$

where P_i^{SSSC} represents the active power injection of the SSSC voltage source at node *i*. The other terms in (9) take account of the real power contribution at node *i* as of a passive two-node component. Analogously, from (6), (7), (8) the expressions of the SSSC reactive power injection at node *i* and the SSSC real and reactive power injections at node *j*, Q_i^{SSSC}, P_j^{SSSC} and Q_j^{SSSC}, respectively, can be extrapolated. They result to be:

$$Q_i^{SSSC} = V_i V_l [G_l \sin(\vartheta_i - \vartheta_l) - B_l \cos(\vartheta_i - \vartheta_l)] \quad (11)$$

$$P_j^{SSSC} = - V_j V_l [G_l \cos(\vartheta_j - \vartheta_l) + B_l \sin(\vartheta_j - \vartheta_l)] \quad (12)$$

$$Q_j^{SSSC} = - V_j V_l [G_l \sin(\vartheta_j - \vartheta_l) - B_l \cos(\vartheta_j - \vartheta_l)] \quad (13)$$

The equality constraint in (3), by (4), gives

$$V_l^2 G_l + V_l V_j [G_l \cos(\vartheta_l - \vartheta_j) + B_l \sin(\vartheta_l - \vartheta_j)] + \\ - V_l V_i [G_l \cos(\vartheta_l - \vartheta_i) + B_l \sin(\vartheta_l - \vartheta_i)] = 0 \quad (14)$$

It can be shown that (14) is equivalent to

$$P_i^{SSSC} + P_j^{SSSC} = 0 \quad (15)$$

by assuming

$$G_l = 0 \quad (16)$$

that is

$$-\varphi_l = \pi/2 \quad (17)$$

The relations (16), (17) mean that the admittance of the SSSC coupling transformer is reactive (conductance neglected). Then, by (10), (11), (12), (13) and the SSSC equality constraint in a diverse form (16), a PIM has been originally built to be a SSSC steady-state model equivalent to the VSM under the assumption (16). Figure 3 shows the PIM equivalent scheme.

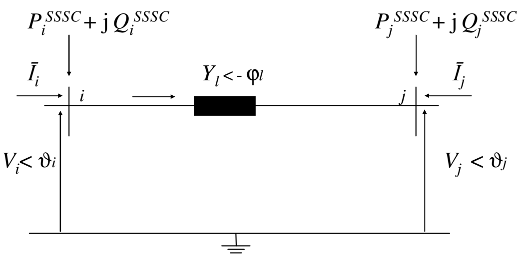

Figure 3: SSSC Power Injection Model.

As it can be seen, in this model the SSSC voltage source has been bypassed and its effects are taken into account by the SSSC power injections at the two nodes. These power injections represent the SSSC controllable variables. Furthermore, the two-node admittance matrix $\dot{Y}$, in presence of SSSC, is symmetric being

$$\dot{Y} = \begin{bmatrix} \dot{Y}_l & -\dot{Y}_l \\ -\dot{Y}_l & \dot{Y}_l \end{bmatrix} \quad (18)$$

In order to implement the SSSC in a network for power system studies, this model can be incorporated into traditional Newton-Raphson load flow algorithms. The SSSC variables combined with the network unknown variables are then adjusted automatically to achieve a Newton's quadratic convergence towards a unified load flow solution including the targets set for the SSSC; these could lead to control one of parameters like the real power flow, the reactive power flow, the line reactance on the SSSC branch, and the voltage amplitude on one of the SSSC connection nodes. In this way, good convergence performances can be also obtained, while keeping an approach in line with the one in [8] for setting initial conditions of SSSC variables and for limits revision.

The PIM here introduced presents the same advantages as those offered by the VSM for SSSC modeling; furthermore, it bypasses the direct presence of the voltage source in the load flow algorithm, keeping the symmetry properties of the system admittance matrix. This leads to a more robust and feasible SSSC model for load flow applications.

A similar approach has been followed in [25][26] to develop original UPFC models for steady-state studies, however the differences in terms of control features and initial conditions setting have to be taken into due account.

2.2 VSC-HVDC

The different features of the self-commutated VSC-HVDC have been analysed in open literature in the recent years (see e.g. [3][9][16] among others). This power electronics-based technology gives the key possibility of independently regulating the real and reactive power flow and also controlling the local bus voltage when inserted in a transmission line. In addition, in contrast to conventional HVDC, VSC-HVDC represents the state-of-the-art technology for offshore wind connection and for multi-terminal applications.

Figure 4 shows the basic scheme of a VSC-HVDC installed on a transmission line ($\overline{V}_i$ and $\overline{V}_j$ represent the complex voltages at the generic nodes *i* and *j*, respectively). It consists of two shunt-connected voltage source converters, based on turn-off power semiconductors as switching elements. VSC 1 acts as rectifier (AC-DC conversion), while VSC 2 behaves as an inverter (DC-AC conversion). The DC circuit links the two converters and can be a line or cable (full VSC-HVDC, as schematized in Figure 4, in which R_{DC} takes account of the DC connector, and C_1 and C_2 are the respective capacitors at converters' sides) or simply a storage capacitor with a very short link (back-to-back VSC-HVDC). The two converters are capable of independently controlling the amount of reactive power exchanged with the respective AC node, and then the local AC bus voltage magnitude. Both converters linked by the DC circuit are also able to control the active power exchanged with the respective AC node, but only one of the two can provide independent active power control, being the other one constrained to keep the DC power balance. In Figure 4, P_{q1}^{spec}, Q_{q1}^{spec}, and P_{q2}^{spec}, Q_{q2}^{spec}, are the specified active and reactive power to be exchanged from each converter, respectively VSC 1 and VSC 2, at the AC output: they define the output voltage angle and magnitude generated by each converter.

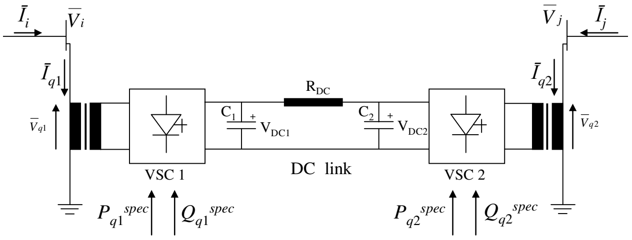

Figure 4: A basic scheme of full VSC-HVDC.

In order to implement VSC-HVDC for steady-state studies, advanced VSC-HVDC representations like the ones provided by the Voltage Source Model (VSM) and the Power Injection Model (PIM) have been taken into account (see [9][10] and the references therein quoted for the VSM and PIM formulation).

Considering a VSC-HVDC simultaneously controlling the real and reactive power flow from the sending bus (for instance, node *i*) and the voltage magnitude at the receiving bus (node *j*) while keeping the DC power balance, a simplified model can be obtained from the VSM and the PIM. By the assumption that the DC link voltages at capacitors C_1 and C_2, V_{DC1} and V_{DC2} (see also Figure 4), are kept practically fixed by the operation of the two converters, the DC power losses, $P_{DC,link}$, due to the DC connector can be considered constant. This term results to be equal to

$$P_{DC,link} = (V_{DC1} - V_{DC2})^2 / R_{DC} \quad (19)$$

for a full VSC-HVDC scheme.

By considering that the DC losses due to the VSC converters can be also assumed to be constant, the total DC side power losses P_{DC} can be then taken as invariant.

In this case, the VSC-HVDC can be modeled by means of a load and a generator, as Figure 5 shows. The sending bus of the VSC-HVDC can be represented as a PQ-node (load) with the active and reactive power loads, P_{ij} and Q_{ij}, set at the values controlled by the VSC-HVDC. The receiving bus can be schematized as a PV-node (generator), accounting for the active power injection P_{ij} and also for the constant DC losses P_{DC}, with the voltage magnitude V_j set at the value controlled by the VSC-HVDC. This decoupled model for VSC-HVDC can be then inserted in standard Newton-Raphson load flow algorithms. After load flow convergence, the VSC-HVDC parameters V_{q1}, ϑ_{q1}, V_{q2}, ϑ_{q2}, which are the respective controllable voltage magnitudes and angles of the VSC 1 and VSC 2, can be computed by solving the set of load flow equations of VSM or PIM [9][10].

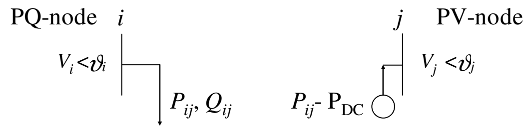

Figure 5: The decoupled model of VSC-HVDC.

2.3 GIL

A Gas Insulated Line (GIL) is a transmission technology composed of pipes housing conductors in highly insulating gases (sulphur hexafluoride SF_6, or with nitrogen N_2 in a N_2/SF_6 gas mixtures), which have high load transfer capacity [20][21].

The basic structure of a GIL is characterised by a conductor at high voltage, which is located within an earthed conducting enclosure and the space between the two elements is filled with a gas under pressure to provide electrical insulation. The conductors of each phase are held in position by solid support insulators and may be located within separate enclosures (single-phase enclosed). The GIL is divided along its length into separate gas compartments. GIL dimensions are determined by dielectric, thermal and mechanical considerations [20]. Figure 6 shows a basic GIL scheme.

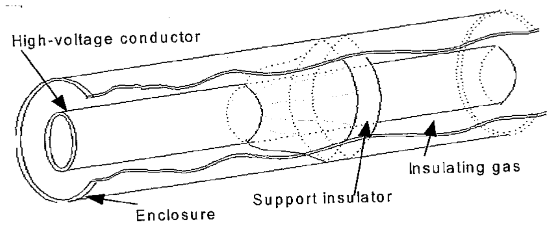

Figure 6: Basic scheme of a GIL [20].

A quite detailed technical literature is available on GIL (see [5][6][20][21] among others). This technology is characterised by a relatively low level of overall losses (due to large conductor cross sections); it also presents no significant dielectric losses. Power ratings of 2000 MVA can be reached by a GIL single circuit, directly buried without cooling. Furthermore, GIL features a low capacitance level per unit length and consequently reactive compensation (for lengths up to 100 km, and even higher) is not needed. GIL, which holds an immunity to weather conditions (snow, ice, wind, pollution), can be possibly installed above ground, in trough/tunnels or can be directly buried [20][21]. This technology is still at prototype/demonstration stage.

For steady-state studies, a GIL can be represented by a π-type transmission model (see Figure 7) with the opportune link parameters. In fact, due to its physical features, the electrical characteristics of a GIL are different with respect to those ones of an overhead line (OHL) or a cable. The resistance R_{GIL} depends on the conductor and enclosure dimensions and electrical resistivities, the skin and proximity effects and the conductor and enclosure temperatures. The shunt conductance G_{GIL} is not significant and can be neglected. The reactance of a GIL, X_{GIL}, is relatively lower than that one of a cable system and much lower than that one of an equivalent overhead line (by a factor of about 5.5 for a single circuit). In a meshed transmission network, GILs may provide a parallel path to OHLs. Due to its lower reactance, GILs will tend to carry a greater share of the transmitted power [20].

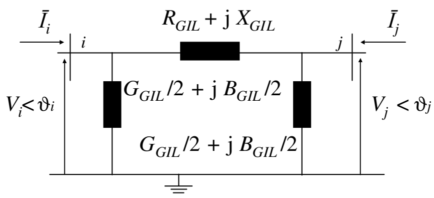

Figure 7: The π-type model of a GIL.

3 ENVIRONMENTAL FEATURES

Due to political restrictions and public environmental awareness, environmental considerations have become an increasingly important part of transmission planning. For this reason, the land use of transmission system components has to be taken into due account. In case of OHLs the term land use refers to the surface area occupied by the tower footing and the span, while in case of cables this term indicates the surface area over the underground cable run. For both the span and the surface area of the cable run, the usability is constricted after construction. For HVDC terminals the term land use refers to the area occupied by the facility buildings. Depending on the technology, other environmental aspects, related e.g. to the electromagnetic emissions, may also need to be evaluated.

3.1 SSSC

FACTS devices have an environmental impact in terms of increased surface occupation in the substations.

The usual range of surface occupation (or land use) due to the installation of SSSCs lies between 5 and 10 m^2 per MVAR, depending on voltage level, power rating, system components and design [3][4][19].

3.2 VSC-HVDC

HVDC transmission generally provides an environmental advantage over HVAC. In fact, an HVDC OHL requires less land occupation than an HVAC OHL with equivalent carrying capacity. In case of OHLs, the width of surface occupation can be significantly reduced by approximately 30 to 50% when choosing HVDC instead of HVAC transmission. Further advantage of HVDC over HVAC is due to its ability to go underground by the use of HVDC cables, especially for longer distances. The use of cables minimizes the visual impact of the transmission line since the surface area over the cable run can be re-naturalized, as long as the cable can be made accessible for maintenance or repair purposes at short notice. Converter stations for traditional HVDC systems require more space than a conventional AC substation for the same transmission capability, while a VSC station occupies quite less space than classic HVDC one [3][9][10][19].

Furthermore, the electromagnetic field emission of HVDC, contrary to HVAC, is not pulsating and can be forced to a minimum value in case a dedicated return conductor is used and the conductor arrangement is selected accordingly. The result is a significantly lower electromagnetic emission, especially in case of OHLs, compared to the electromagnetic emissions by conventional HVAC transmission. The acoustic emission of HVDC stations has to be considered but can be reduced to comply with the legal requirements by an indoor station design [3][19].

3.3 GIL

A GIL installation requires sufficient space along the link for the pipes (enclosures), each containing the respective conductor. For each phase a pipe of outer diameter of typically 0.7 m ca. is necessary at 400 kV. The minimum space between each pipe is ca. 0.6 m [22].

In a GIL, due to a reverse current of the same level induced in the enclosure, the electromagnetic field outside the GIL is negligible. Therefore, no special shielding is required even in areas which are critical with respect to electromagnetic fields.

If an insulation failure would occur inside a GIL, the fault arc remains inside the enclosure and does not influence outside equipments or persons. GILs are fire resistant and do not contribute to fire load. This is a crucial aspect where the connection between OHL and high voltage switchgear goes through tunnels and shafts.

The first generation of GILs used pure SF_6, an inert, non-toxic, non-flammable gas, for insulation. However, as SF_6 is very expensive and contributes to greenhouse gas, in a new generation of GIL applications (designed for long distances), N_2/SF_6 gas mixtures are more optimally used (generally in a proportion of 80% N_2 and 20% SF_6). These gas mixtures are suitable for reducing the costs of the equipment as well as the impact of SF_6 leakage. N_2 is a cheap, inert, non-toxic, non-flammable gas, and it is environmentally acceptable [20]-[22].

4 ECONOMIC FEATURES

Capital expenditures for transmission system assets are highly dependent on different parameters, such as equipment type, rating and operating voltage, technology maturity, local environmental constraints, population density and geographical characteristics of the installation area as well as costs of material, manpower and right-of-way. In general, environmental constraints increase costs and implementation time - e.g. for OHL - while technological advances in manufacturing usually reduce costs: this is the case for power electronics components or for underground XLPE (Cross-Linked Polyethylene Extruded) cables. Another aspect that plays a role in the determination of transmission assets costs (especially for innovative technologies) is that equipment prices continuously change due to a dynamic world market: costs of European transmission assets are then influenced and driven by external factors. In order to take into account all these factors, Table 1 reports up-to-date (average) ranges for the costs of different 400 kV transmission components in continental Europe in standard installation conditions [3][19][22].

In Table 1 the lower limit (min value) refers to installation costs in continental European countries with low labour costs (like e.g. in southern or eastern Europe), while the upper limit (max value) refers to installation costs in European countries with high labour costs (like e.g. France, Netherlands or Germany). Costs for OHLs refer to the base case, wherein the installation of OHLs over flat landscape and in sparsely populated areas is considered. Costs for installations over hilly and averagely populated land as well as over mountains or densely populated areas are to be taken into account by a surcharge of +20% and +50%, respectively. In the case of underground cables and GILs, the cost component related to the installation expenditure can very much influence the final investment cost, depending on installation location, type of terrain and other local conditions [22].

Cost of components	Rating	Min	Max	Unit
HVAC OHL (single circuit)	1500 MVA	400	700	kEUR/km
HVAC OHL (double circuit)	3000 MVA	500	1000	kEUR/km
HVAC underground XLPE cable (single circuit)	1000 MVA	1000	3000	kEUR/km
HVAC underground XLPE cable (double circuit)	2000 MVA	2000	5000	kEUR/km
HVAC GIL (double circuit)	2000 MVA	4000	7000	kEUR/km
HVDC OHL bipolar	1000 MW	300	700	kEUR/km
HVDC underground XLPE cable (pair)	1000 MW	700	2000	kEUR/km
VSC converter terminal (bipolar)	1000 MW	75000	125000	kEUR
CSC converter terminal (bipolar)	1000 MW	70000	110000	kEUR
SSSC	140 MVAR	7000	11200	kEUR
local compensations (% installation costs)		10	20	%

Table 1: Average capital costs (range) of transmission assets.

The cost ranges provided for HVDC converter equipment are presented "per terminal", wherein a terminal includes all equipment at one side of the bipolar transmission line: both converters, reactive compensation (if needed), active filtering, AC/DC switchgear, engineering, project planning, taxes etc. except any costs related to the transmission medium. In fact, it has to be noted that, on the one hand, VSC-HVDC is by nature bipolar; on the other hand, bipolar HVDC installations are preferred within a synchronized power grid for system security reasons.

In general, a project requires an initial investment, which is then gradually recovered by means of the earnings coming from the implemented project. The project earnings translate the benefits provided by a transmission investment into monetary terms. These benefits can be generally grouped as: system reliability, quality and security increase; system losses reduction; congestion reduction and market benefits; environmental sustainability benefits; avoidance/postponement of investments; more efficient reserve management and frequency regulation; improvement of the dynamic behaviour of the power system [24].

The reduction of network congestions, which may result from transmission capacity enhancement, is a key benefit possibly deriving from transmission expansion. This would then allow the exploitation of transmission corridors and the consequent unlock of more efficient power generation ('substitution effect'), both within one market and on a multi-national basis. When planning fast power flow controllers such as FACTS and HVDC devices, an additional benefit is the power flow controllability increase granted by these technologies.

In case the transmission of a higher level of power between two zones is of concern, TSOs (Transmission System Operators) may choose the most appropriate solution(s) among a portfolio of conventional and innovative transmission technologies. A solution may be for example the deployment of a VSC-HVDC link or of a GIL, also depending on local conditions and different types of constraints. The transmission expansion advantages which will be quantified in the following analysis are:

- Congestion reduction by transmission capacity enhancement, monetized in terms of increased cheaper energy imported by a zone or country with a higher electricity wholesale price;
- Additional energy exchange secured by fast controlling devices and monetized in terms of increased cheaper energy imported by a zone or country with a higher electricity wholesale price.

The latter benefit is achievable by devices like SSSC and VSC-HVDC due to their control properties. SSSC and VSC-HVDC may also offer other advantages, here not quantified, such as e.g.: punctual support to reactive power and voltage control; avoidance/reduction of undesired power flows [10][18].

The above economic benefits can be measured by an increase of the total Social Welfare (SW) due to the investigated expansion project [24]; the SW can be generally defined as the difference between the global benefit of the energy to consumers, given by their willingness to pay for it, and the sum of all generation costs for producing the same energy.

Considering only the contribution to SW from congestion revenues, the above benefits can be expressed in this case in a simple way as

$$\Delta CR = h_2 \, \Delta\lambda_2 \, NTC_2 - h_1 \, \Delta\lambda_1 \, NTC_1 \quad (20)$$

where: ΔCR indicates the congestion revenue differential between the situations in presence and in absence of the investigated transmission expansion asset; $\Delta\lambda_1$ and $\Delta\lambda_2$ represent the electricity price differential between the importing and the exporting system before and after the interconnection installation, respectively; NTC_1 and NTC_2 express the transmission capacity available in secure conditions and granted by the new asset before and after the interconnection installation, respectively; h_1 and h_2 represent the yearly utilisation hours of that asset providing NTC_1 and NTC_2

before and after the interconnection installation, respectively (h_1 and NTC_1 may also be null in absence of interconnections between the investigated systems as starting condition). The NTC (Net Transfer Capacity) can be defined as the maximum power transfer between two zones compatible with (n-1) security standards applicable in both zones and taking into account the technical uncertainties on future network conditions. The NTC differs from the Total Transfer Capacity (TTC) by a security margin, the Transmission Reliability Margin (TRM) [9][10][18][23].

The future revenues have to be discounted according to the expected accumulated inflation and interest rates. The comparison and prioritisation of alternative solutions is performed via cost-benefit analyses based on the following well known indicators:

- Net Present Value (NPV) of an investment
- Internal Rate of Return (IRR) of the invested capital
- Profitability Index (PI) of an investment
- Pay Back Period (PBP) of an investment

5 TEST RESULTS

In this Section, the results of various network studies and cost-benefit analyses implementing the different models of SSSC, VSC-HVDC and GIL are presented. Load flow simulations have been carried out in Matlab® on two test networks: the IEEE 30-bus system and the transmission grid of Continental Europe (former UCTE) part of the ENTSO-E [23]. The latter test network (at 400-220 kV) is based on the one described in [17] consisting of 1254 buses, 378 generators and 1944 lines and conveniently approximating the continental European system behaviour, especially concerning the cross-border flows. For this system, considering the winter peak condition, the line capacity limits have been updated with data available from [23] (2008) as well as recent upgrades have been taken into account.

5.1 SSSC modeling validation: IEEE 30-bus network

The validation of the new SSSC PIM (presented in Section 2.1) for steady-state studies has been firstly carried out by testing the model for load flow implementations on the IEEE 30-bus network. This system comprises 6 generators, 4 transformers and 41 branches. The goal is to compare the results obtained by implementing the original PIM with those ones by the known VSM presented in [8]. Like in [8], a lossless SSSC has been inserted into the line 12-15 with the objective to control the active power flow towards bus 15 at 30 MW, which is a more than 60% increase respect to the base case (without SSSC the active power flow from bus 12 towards bus 15 is in fact equal to 18.4 MW). In this case, an additional node, bus 31, is needed to connect the SSSC and the device is actually on the line 12-31. Utilizing SSSC parameters rates such as $\dot{Y}_l$ =-j/0.1 p.u. and 0 p.u.$\leq V_l \leq$ 0.2 p.u., the load flow results obtained by implementing both the models, VSM and PIM, are identical and the SSSC control target has been reached, as the power flows result to be 30 MW + j6.67 MVAR from bus 12 to bus 31 and -30 MW - j8.14 MVAR from bus 31 to bus 12, respectively. Convergence of Newton-Raphson load flow algorithm has been achieved to a tolerance of 10^{-12} p.u. (or 10^{-10} MW/MVAR) within the same number of iterations (7) by both VSM and PIM. Given the chosen SSSC parameters rates, no constraint violation, unlike the corresponding case in [8], is observed. Table 2 and Table 3 show the complex voltages for the concerned network buses and the SSSC variables' values, respectively, obtained by both the VSM and the PIM for the investigated IEEE 30-bus system tests.

Bus	12	31	15
V (p.u.)	1.049	1.061	1.033
ϑ (deg.)	-15.61	-12.97	-14.74

Table 2: Complex voltages by VSM and PIM.

By the PIM the SSSC real and reactive power injections at SSSC nodes 12 and 31 result to be -81.17 MW, -18.1 MVAR, and 81.17 MW, 22.0 MVAR, respectively. As the results in the tables coincide, the equivalence among the two SSSC steady-state models, VSM and PIM, in the lossless case is confirmed. Furthermore, all the advantages given by the VSM are present in the PIM, but the PIM offers a greater robustness and feasibility.

Voltage		Power rates (series)	
V_l (p.u.)	ϑ_l (deg.)	P_l (MW)	Q_l (MVAR)
0.07927	-118.15	0	2.32

Table 3: SSSC variables' values by VSM and PIM.

5.2 SSSC application in the European power system

The implementation of SSSC modeling (presented in Section 2.1) is here extended to be applied to the continental European power system. It is important to remark that the first SSSC project in Europe is currently ongoing within the Spanish 220 kV transmission network [4]. Further applications may be foreseen in a short-mid term in other European countries, especially to facilitate the RES integration. A particular case is given by the Polish system, where several reinforcements as well as shunt/series conventional and FACTS devices are needed and planned up to 2020, as stated by the ENTSO-E's Ten-Year Network Development Plan 2010-2020 [23].

In the examined case, attention has been paid especially to the regional power transmission system of Poland (PL) and its cross-border ties with Czech Republic (CZ) and Slovakia (SK). Figure 8 depicts a schematic representation of this part of the test network at 400 kV level [23]. In particular, focus is on the only currently existing link on the PL-SK interface at 400 kV, namely the double circuit OHL Krosno-Iskrzynia (PL) – Lemešany (SK). This double line could theoretically transport up to a maximum of 2x1252 MVA capacity, but due to the presence of network constraints (current transformer) the transfer capacity that the link can securely guarantee is lower being limited to 2x831 MVA. By carrying out power system studies on the continental European power grid in lossless conditions, a Newton-Raphson load flow convergence to a tolerance of 10^{-10} p.u. (or 10^{-8} MW/MVAR) can be reached within 8 iterations. In this starting situation, the PL-SK cross-border tie features power flows of 249.2 MW + j 25.5 MVAR towards south, and of -249.2 MW - j 14.2 MVAR in opposite direction. The goal here is to implement a lossless SSSC (modeled by VSM and PIM) on the PL-SK 400 kV link and evaluate its effects towards an increasing exploitation of the corridor under investigation.

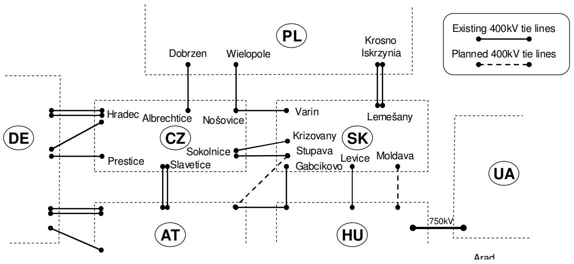

Figure 8: Cross-border tie lines in Central Europe (2008).

Taking into account the different system requirements and device design limits, by utilising SSSC ratings such as $\dot{Y}_l$ =-j/0.02 p.u. and 0 p.u.$\leq$ V_l $\leq$ 0.35 p.u., the SSSC allows an increase of NTC on the PL-SK tie equal to 150 MW in secure conditions. Convergence of Newton-Raphson load flow algorithm has been achieved to a tolerance of 10^{-10} p.u. (or 10^{-8} MW/MVAR) within 22 iterations. Given the chosen SSSC parameters rates, Table 4 shows the SSSC variables' values, obtained by application of both the VSM and the PIM to the European power system towards the NTC enhancement of the PL-SK tie.

Voltage		Power rates (series)	
V_l (p.u.)	ϑ_l (deg.)	P_l (MW)	Q_l (MVAR)
0.319	48.38	0	133.89

Table 4: SSSC variables' values for the PL-SK tie case.

A SSSC designed for a rate of 140 MVAR is then suitable for achieving a ΔNTC of 150 MW on the PL-SK cross-border link. For a techno-economic assessment of the selected device, an investment cost of 9100 k€ (average value in the cost range shown in Table 1, Section 4) is considered, whereas local compensation costs amount to 10% of investment expenditure. Yearly expenses for device operation, maintenance and losses are taken into account by a fixed quota of 5% of investment cost. Assuming a price differential $\Delta\lambda_{SK\text{-}PL}$ equal to 2 €/MWh constant over the observation timeframe (20 years starting from 2015) and a yearly amount of device utilisation hours of 7000 h, with a 10% discount rate, a NPV of 3849 k€, an IRR of 15%, a PI of 1.4 and a PBP of 10 years can be calculated for such SSSC investment. In this analysis, other benefits possibly provided by SSSC have not been evaluated.

5.3 *VSC-HVDC vs. GIL: the Italy-Austria link*

Another application in the European power system is aimed here at a cost-benefit analysis (techno-economic assessment) to compare advanced transmission technologies like the VSC-HVDC and the GIL. This technology comparison refers in particular to the planned new interconnection between Italy (IT) and Austria (AT): these two countries are currently interlinked by the only 220 kV OHL Soverzene (IT) – Lienz (AT), having a limited capability. In the past years, Austria became a country in the centre of the interconnected continental European network in the frame of the opening of the electricity markets. In response, the Austrian TSO had to start the construction of the Austrian 400 kV transmission network. As a result, this country will be crossed by increased north to south transits involving Germany, Slovakia, Hungary but also Slovenia and Italy. This situation is projected to be even more critical in the coming years due to massive integration of RES (wind) in Northern Europe that will cause additional transits from Germany towards south via Austria. Also for this reason, cross-border links at 400 kV between Italy and Austria are absolutely necessary.

In this context, various studies and investigations [5][6][22] have been previously conducted to analyse the technical and environmental possibilities offered by a new IT-AT power link at 400 kV under the Brenner Tunnel. In fact, the new planned railway galleries between Fortezza/Franzensfeste (IT) and Innsbruck (AT) may represent, besides an important step towards the lightening of the transports via highway, also a unique opportunity for considerable power exchanges by means of the installation of a GIL in the "pilot tunnel". However, this project can be considered only in a mid-long term time perspective (after 2020) as several reinforcements/upgrades in both the Italian and the Austrian networks would be needed beforehand. The project would then be the opportunity to rationalize in Austria the development of the local networks existing presently at a voltage lower than 400 or 220 kV and to better integrate the local hydro generation. However, some additional links would be necessary notably in Austria due to the increase of internal transit. On the Italian side there are plans under study to connect the tunnel entry (Fortezza/Franzensfeste) with the 400 kV Italian network by extending the local 220 kV to 400 kV (Fortezza/Franzensfeste – Bolzano/Bozen - Nogarole axis), as shown in Figure 9 [22].

Within this background, for the same Brenner Tunnel (65 km long) features and installation conditions as described in [5][6][22], a VSC-HVDC link is also here considered as a transmission option alternative to the GIL. Option 1 is then based on a double-circuit GIL rated 2000 MVA, while Option 2 represents a 2x1000 MW VSC-HVDC system. A VSC-HVDC link has been utilized as modeled in Section 2.2. The VSC-HVDC control has been supposed to keep V_{DC1} and V_{DC2} respectively at 98% and 100% of their nominal values.

The GIL is modeled by the simple scheme introduced in Section 2.3 with the GIL parameters used in [6].

Both options can be able to achieve a ΔNTC of 1800 MW on the IT-AT cross-border link. Additionally, due to its fast control features, VSC-HVDC is also able to guarantee an extra 200 MW of transfer capacity. For a techno-economic comparison of the two options, the minimum and maximum value of local compensation and investment costs (in the cost range shown in Table 1, Section 4) are both considered: in this way, the options are totally four. For the GIL options (Option 1-Min and Option 1-Max) yearly expenses for device operation and maintenance, on one hand, and losses, on the other hand, are respectively taken into account by fixed values of 0.1% of investment cost and 6825 kW remunerated at 0.04 €/kWh [22]. For the VSC-HVDC options (Option 2-Min and Option 2-Max) yearly expenses for device operation and maintenance, on one hand, and losses, on the other hand, are respectively taken into account by fixed values of 2.0% of investment cost and 40000 kW remunerated at 0.04 €/kWh for each VSC-HVDC system. These figures for VSC-HVDC take also account of the converters [3].

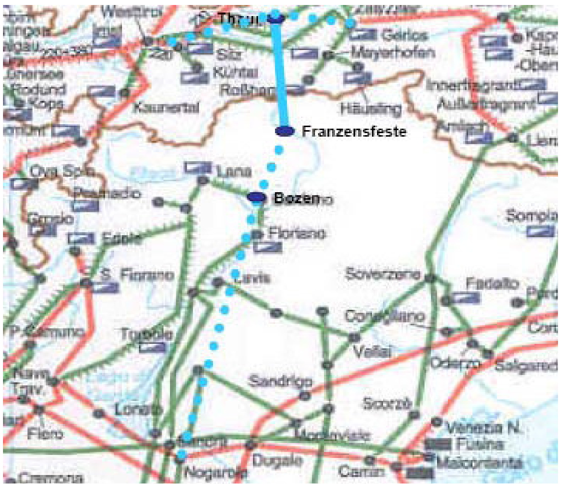

Figure 9: Variant for extending the 400 kV grid in Italy.

In the following, a starting value (before the asset installation) for the price differential $\Delta\lambda_{1,\ IT\text{-}AT}$ has been considered to be equal to 15 €/MWh (it is currently 20 €/MWh on average [1]). A price differential $\Delta\lambda_{2,IT\text{-}AT}$ (after the asset installation) has been chosen as a parametric variable for the analysis. This can be equal to four values (3, 6, 9, and 12 €/MWh) for the calculation of ΔCR in (20), with an observation timeframe of 20 years (starting from 2020) and a yearly amount of link utilisation hours of 7000 h. By adopting a 10% discount rate, the results of the techno-economic analysis provide that in general the GIL options are more convenient than the VSC-HVDC ones. This occurs especially for limited values of $\Delta\lambda_{2,IT\text{-}AT}$ whereas the convenience of VSC-HVDC is higher with an increasing value of $\Delta\lambda_{2,IT\text{-}AT}$. In general, in addition to the techno-economic analysis, also the investigation of environmental aspects (some of them are treated in Section 3) shall be carried out to provide the transmission planners with further elements for their decision-making. In this case, in terms of land occupation (footprint), upon installation GIL may be slightly preferable over VSC-HVDC due to the need for four HVDC converters, while more space is required by GIL during the installation. Also, GIL may be penalised because of SF_6 gas leakage risk.

Finally, other types of analyses and considerations (related to technology features, maturity, price reduction trend, efficiency, controllability, integration ability etc.) may be complementarily needed and conducted as well towards the planners' decision-making.

6 CONCLUSIONS

The present paper has investigated several technical, environmental, and economic features of three types of advanced transmission technologies, namely the SSSC, the VSC-HVDC and the GIL, currently having a different level of maturity and deployment in Europe. In order to apply these advanced technologies in the future European power system, steady-state modeling represents an essential stage. Also, an original SSSC model has been introduced and validated in this paper. Techno-economic analyses for implementing SSSC and for comparing VSC-HVDC and GIL in targeted applications in the future European system have been then carried out.

Future work, also in the frame of REALISEGRID project [2], will assess further transmission expansion benefits [24] towards the realisation of an optimisation-based methodology for a comprehensive cost-benefit analysis. This should duly translate the measured benefits (among the ones listed in Section 4) in monetary terms. Also, further innovative technologies will be modeled and applied as well as wider tests at European system scale for long-term simulation runs will be carried out. Further work will be also performed for dynamic studies of advanced technologies (including FACTS and HVDC).

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'The results presented in this paper - also because of the different assumptions, conditions and data considered - may differ from those ones obtained in studies of the relevant stakeholders on the Italy-Austria Brenner tunnel project. The views expressed in this paper are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission'.