

# MODELING AND APPLICATION OF VSC-HVDC IN THE EUROPEAN TRANSMISSION SYSTEM

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**Abstract** – The present paper focuses on the technical, environmental, and economic features of VSC-based HVDC technologies. The aim is to investigate the impact of VSC-HVDC on the European power system: specific attention is paid to the transmission capacity enhancement attainable in targeted applications. Towards this purpose, an original steady state model of the VSC-HVDC is presented and tested. Then, a techno-economic analysis of the impact of VSC-HVDC on liberalized power systems in Europe is undertaken so as to investigate the feasibility and the sustainability of such investment, also compared to building HVAC lines.

**Keywords:** *analysis of investments, European power system liberalization, VSC-HVDC, power flow analysis, steady state modeling, transmission capacity enhancement, transmission planning*

## 1 INTRODUCTION

The electric power systems are generally experiencing different trends which may imply major changes in both their architecture and operation.

In Europe, against a background of energy market restructuring, increasing environmental awareness and rising concerns about security of energy supply, the electric power grid is facing several issues.

Indeed, due to a general increase of inter- and intra-zonal power transactions, the transmission network in some areas operates close to its physical limits [1]. Furthermore, the constant growth in electricity demand in Europe can put the electric system under strain. Such issues have been traditionally addressed by adding new capacity, with investments particularly in the field of large-size generation and High Voltage Alternating Current (HVAC) transmission infrastructures.

Nowadays, increasing the power system capacity is frequently a challenging option due to economic, environmental, and political constraints that hinder the construction of large power plants and high voltage lines. To address the above issues new solutions are therefore sought necessary. Among them, one of the most promising foresees the targeted deployment of HVDC (High Voltage Direct Current) transmission technologies displacing the conventional HVAC ones [2][3]. The land use and the environmental impact as a whole may be smaller with HVDC compared to HVAC technology.

In any case, a techno-economic assessment needs to be carefully carried out by taking into account the relevant attached cost and benefit elements. HVDC is a well established technology and presents characteristics that have made it widely attractive over AC transmission for specific applications like long-distance power transmission, long submarine cable links and interconnection of asynchronous systems [2][3].

Currently, recent advances in the power electronics, coupled to the traditional features of HVDC, may lead to improve the operation and sustain the development of the European transmission grid. In fact, the application of VSC (Voltage Source Converter)-based HVDC can provide the European power system with an increased transmission network capacity and generally enhanced system reliability, security and controllability [3]-[5]. These properties are especially important in a deregulated environment: VSC-HVDC with its fast power flow control capability can be an attractive option to efficiently and timely avoid or relieve network constraints, thus reducing the need for building new HVAC lines.

The present paper aims at investigating the impact of VSC-HVDC on the European power system, focusing on the technical, environmental, and economic features of these devices. Specific attention is paid to the transmission capacity enhancement attainable by VSC-HVDC in targeted applications in the European power system. Towards this scope, modeling VSC-HVDC technologies for steady-state studies becomes essential. A techno-economic analysis of the impact of VSC-HVDC on liberalized power systems in Europe is also undertaken to investigate the feasibility and the sustainability of such investment, also compared to other alternatives such as building or replacing AC lines.

In this paper, Section 2 presents the main technical features of VSC-HVDC. Section 3 introduces an original VSC-HVDC Power Injection Model (PIM) suitable for load flow studies. Section 4 deals with the introduction of VSC-HVDC economic and environmental features. Section 5 first presents load flow test results successfully validating the features of PIM. Finally, the outcomes of practical test cases towards a techno-economic assessment of VSC-HVDC are shown. Focus is particularly on the enhancement of cross-border

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transmission capacity in a European regional market system.

## 2 TECHNICAL FEATURES OF VSC-HVDC

The traditional HVDC technology has been deployed especially for overhead bulk power transmission over long distances and undersea cable connection. The HVDC links present in Europe are mostly submarine cables connecting various power system portions separated by sea (e.g. Scandinavia - mainland Europe, UK - France, UK - Ireland, Italy - Greece). Indeed, for overhead transmission, the HVAC lines have so far offered a more viable techno-economic solution with respect to HVDC to cover small and medium distances (below some hundred km) [2][3].

An innovative HVDC technology - based on Voltage Source Converters (VSCs) and therefore called VSC-HVDC - has been recently applied not only to overcome critical issues hindering the upgrading/construction of HVAC lines but also to increase the robustness of the transmission system. VSC-HVDC units currently range from a few tens of MW to several hundreds (up to a thousand) of MW and can reach  $\pm 300$  kV voltages. The most recent installation of VSC-HVDC in Europe has been the submarine link between Finland and Estonia (Estlink) [5], while more projects are ongoing/planned; also, plans for overland installation start to be discussed in several countries.

The characteristics of VSC-HVDC have been recently investigated in open literature ([3]-[5],[6][7] among others). The key advantages of VSC-HVDC, in comparison with the classic HVDC based on Current Source Converters (CSCs) are described in [3]-[5].

*Flexibility and range of power control.* VSC-HVDC can control both active and reactive power independently, differently from classic HVDC, and generate or consume reactive power within a wider range than HVDC by a very rapid control action. This is because VSC-HVDC converter stations employ state-of-the-art power semiconductors such as Gate Turn-Off (GTO) Thyristors, Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated Thyristors (IGCT), which are also capable to turn off the current. The VSC-HVDC makes it possible to create almost instantaneously any voltage phase angle or amplitude. Both stations can independently generate or consume reactive power. Unlike conventional HVDC converters, which normally have a 5% minimum current, the VSC-HVDC can operate even at zero active power and in this situation still provide the full range of reactive power. The power reversal is obtained by changing the direction of the direct current (DC) and not by changing the DC voltage as for conventional HVDC.

*Compactness and modularity of converter stations.* VSC-HVDC is based on a modular concept with standardized sizes for the converter stations. Conventional HVDC is generally tailor-made to suit specific applications. Compared with the classic HVDC station, the

converter station with VSC is more compact and has a smaller footprint. Modular systems can be installed in different stages to meet the capacity demand.

*Easier expansibility to multiterminal configurations.*

In contrast to conventional HVDC, with VSC-HVDC it is easier to connect substations to a generic point of the line, whereby getting a DC line with multiple terminals. The costs are those of a single converter per tapping. Costs are naturally lower when the new substation is not sized to carry the full load. Compared to CSCs, the VSC technology facilitates the connection of several converters to a common bipolar DC bus since the voltage polarity is not reversed when changing the power direction.

Naturally, the VSC-HVDC technology presents also some drawbacks when compared to HVDC and the main ones are portrayed in the following.

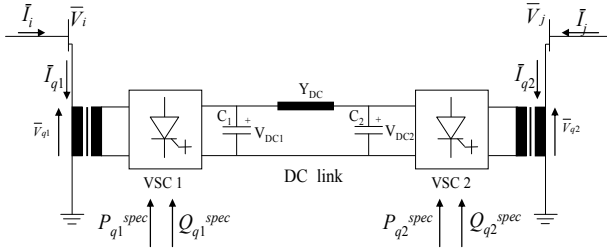
- VSC-HVDC technology is more expensive than traditional HVDC, basically due to the higher cost of the converter stations.
- VSC-HVDC technology displays higher converter losses than traditional HVDC (some 1-2% of system rated power). Consequently, for a given transmission capacity, the cable length that equals the AC Overhead Line (OHL) systems losses (the so-called break-even distance) is higher than that for HVDC.
- VSC-HVDC is by nature bipolar since the DC circuit is not connected to ground. Differently from traditional bipolar HVDC, VSC-HVDC has no possibility to execute emergency power transfer via one pole when the other pole trips.
- DC line-to-ground faults are more critical with VSC-HVDC than with CSC-HVDC.

However, considering the intrinsic features of VSC-HVDC and the steady advances in such technological field, it is expected that some disadvantages can be quickly scaled down and others overcome.

## 3 VSC-HVDC MODELING

Figure 1 shows the basic scheme of a VSC-HVDC installed on a transmission line ( $\bar{V}_i$  and  $\bar{V}_j$  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 transformation), while VSC 2 behaves as an inverter (DC-AC transformation). The DC circuit links the two converters and can be a line or cable (full VSC-HVDC, as schematized in Figure 1, in which  $Y_{DC}$  takes account of the DC connector, and  $C_1$  and  $C_2$  are the respective capacitors at converters' sides) or simply a storage capacitor (back-to-back VSC-HVDC). In the latter case, the back-to-back VSC-based system coincides with a scheme of two shunt-connected FACTS (Flexible AC Transmission System) devices like STATCOMs linked by a capacitor [8]. 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 (so-called primary or master converter) can provide independent active power control, being then the other one (so-called secondary or slave converter) constrained to keep the DC power balance [6][7]. In Figure 1  $P_{q1}^{spec}$ ,  $Q_{q1}^{spec}$ , 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 1:** A basic scheme of full VSC-HVDC.

In order to model the VSC-HVDC for steady-state studies the equivalent representation shown in Figure 2 has been taken into account. It leads to a known VSC-HVDC model which can be referred to as Voltage Source Model (VSM) [6][7].

In the VSM representation, considering exclusively the VSC-HVDC in a line linking the nodes  $i$  and  $j$ , the equivalent circuit consists of two voltage sources,  $\bar{V}_{q1}$  and  $\bar{V}_{q2}$ , with the respective leakage admittances,  $\dot{Y}_{q1}$  and  $\dot{Y}_{q2}$ , of the coupling transformers at the two shunt converter terminals. Assuming that the voltage sources are ideal (that is, harmonics are neglected here), they are:

$$\bar{V}_{q1} = V_{q1} (\cos \vartheta_{q1} + j \sin \vartheta_{q1}) \quad (1)$$

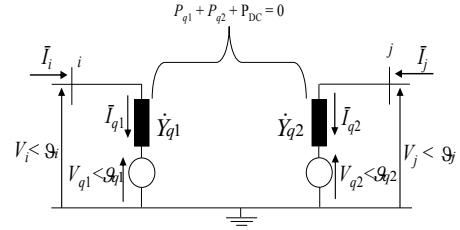
$$\bar{V}_{q2} = V_{q2} (\cos \vartheta_{q2} + j \sin \vartheta_{q2}) \quad (2)$$

where  $V_{q1}$ ,  $\vartheta_{q1}$ ,  $V_{q2}$ ,  $\vartheta_{q2}$  are the controllable voltage magnitudes and angles of the VSC 1 and VSC 2, respectively. These controllable parameters have the following limits:  $V_{q1 \min} \leq V_{q1} \leq V_{q1 \max}$ ,  $0 \leq \vartheta_{q1} \leq 2\pi$ , for VSC 1, and  $V_{q2 \min} \leq V_{q2} \leq V_{q2 \max}$ ,  $0 \leq \vartheta_{q2} \leq 2\pi$ , for VSC 2, respectively. The coupling admittances,  $\dot{Y}_{q1}$  and  $\dot{Y}_{q2}$ , of the two converters can be respectively expressed by

$$\dot{Y}_{q1} = G_{q1} + jB_{q1} \quad (3)$$

$$\dot{Y}_{q2} = G_{q2} + jB_{q2} \quad (4)$$

where  $G_{q1}$ ,  $B_{q1}$ , and  $G_{q2}$ ,  $B_{q2}$ , are the coupling conductance and susceptance of the VSC 1 and VSC 2, respectively. In [6] it has been described how to incorporate the converters losses in the VSM for a multiterminal VSC-HVDC.



**Figure 2:** The Voltage Source Model (VSM) of VSC-HVDC.

By the assumption that the DC link voltages,  $V_{DC1}$  and  $V_{DC2}$ , are kept constant by the operation of the two converters and taking account of the only resistive part of the DC connector, the DC power losses can be considered practically constant. To maintain the DC power balance, that is the active power flowing from the sending bus (for instance, node  $i$ ) has to equal the sum of active power delivered to the receiving bus (for instance, node  $j$ ) and the DC side losses (from the DC connector and the VSCs). Then, the following equality constraint has to be guaranteed:

$$P_{q1} + P_{q2} + P_{DC} = 0 \quad (5)$$

where  $P_{q1}$ ,  $P_{q2}$ ,  $P_{DC}$  represent the active power at VSC 1, VSC 2 and the DC side power losses, respectively.

Eq. (5) is a necessary equality constraint to be considered in the VSM of VSC-HVDC.

As previously said, under the above assumption and with converter losses neglected, the term  $P_{DC}$  results to be constant and equal to

$$P_{DC} = (V_{DC1} - V_{DC2})^2 / R_{DC} \quad (6)$$

for a full VSC-HVDC scheme, while for a back-to-back VSC-HVDC it is obviously that

$$P_{DC} = 0 \quad (7)$$

The same result as in (7) is also valid for a full VSC-HVDC scheme if all DC losses are neglected. In (6),  $V_{DC1}$ ,  $V_{DC2}$  represent the DC voltages at capacitors  $C_1$  and  $C_2$  in a full VSC-HVDC (see also Figure 1) and  $R_{DC}$  is the resistance of the DC connector.

Despite its various advantages [6][7], the VSM introduces some difficulties in modeling the system with embedded VSC-HVDC devices due to the presence of the voltage sources. In fact, in order to have a square admittance matrix, the introduction of two fictitious nodes is needed for each VSC-HVDC. Furthermore, the symmetry properties of the admittance matrix are lost. A more robust and feasible alternative to the VSM is then needed for VSC-HVDC load flow implementation.

From the scheme of VSM (see Figure 2) and considering (1)-(4), the active power absorbed respectively by the VSC 1 and VSC 2 can be calculated as

$$P_{q1} = -G_{q1}V_{q1}^2 + G_{q1}V_{q1}V_i \cos(\vartheta_{q1} - \vartheta_i) + B_{q1}V_{q1}V_i \sin(\vartheta_{q1} - \vartheta_i) \quad (8)$$

$$P_{q2} = -G_{q2}V_{q2}^2 + G_{q2}V_{q2}V_j \cos(\vartheta_{q2} - \vartheta_j) + B_{q2}V_{q2}V_j \sin(\vartheta_{q2} - \vartheta_j) \quad (9)$$

Also, the load flow equations at nodes  $i$ ,  $j$  can be obtained respectively as

$$P_i = G_{q1}V_i^2 - G_{q1}V_iV_{q1} \cos(\vartheta_i - \vartheta_{q1}) - B_{q1}V_iV_{q1} \sin(\vartheta_i - \vartheta_{q1}) \quad (10)$$

$$Q_i = -B_{q1}V_i^2 - G_{q1}V_iV_{q1}\sin(\vartheta_i - \vartheta_{q1}) + B_{q1}V_iV_{q1}\cos(\vartheta_i - \vartheta_{q1}) \quad (11)$$

$$P_j = G_{q2}V_j^2 - G_{q2}V_jV_{q2}\cos(\vartheta_j - \vartheta_{q2}) - B_{q2}V_jV_{q2}\sin(\vartheta_j - \vartheta_{q2}) \quad (12)$$

$$Q_j = -B_{q2}V_j^2 - G_{q2}V_jV_{q2}\sin(\vartheta_j - \vartheta_{q2}) + B_{q2}V_jV_{q2}\cos(\vartheta_j - \vartheta_{q2}) \quad (13)$$

The eq. (10) can be written as

$$P_i = G_{q1}V_i^2 - P_i^{VSC} \quad (14)$$

with

$$P_i^{VSC} = G_{q1}V_iV_{q1}\cos(\vartheta_i - \vartheta_{q1}) + B_{q1}V_iV_{q1}\sin(\vartheta_i - \vartheta_{q1}) \quad (15)$$

where  $P_i^{VSC}$  represents the active power injection of the VSC 1 at node  $i$ . The other term in (14) takes the real power contribution into account as of a passive two-node component. Analogously, the eqs. (11)-(13) give the expressions of the VSC 1 reactive power injection at node  $i$ ,  $Q_i^{VSC}$ , and the VSC 2 real and reactive power injections at node  $j$ ,  $P_j^{VSC}$  and  $Q_j^{VSC}$ , respectively. They result to be:

$$Q_i^{VSC} = G_{q1}V_iV_{q1}\sin(\vartheta_i - \vartheta_{q1}) - B_{q1}V_iV_{q1}\cos(\vartheta_i - \vartheta_{q1}) \quad (16)$$

$$P_j^{VSC} = G_{q2}V_jV_{q2}\cos(\vartheta_j - \vartheta_{q2}) + B_{q2}V_jV_{q2}\sin(\vartheta_j - \vartheta_{q2}) \quad (17)$$

$$Q_j^{VSC} = G_{q2}V_jV_{q2}\sin(\vartheta_j - \vartheta_{q2}) - B_{q2}V_jV_{q2}\cos(\vartheta_j - \vartheta_{q2}) \quad (18)$$

The equality constraint in (5), by the expressions of  $P_{q1}$ ,  $P_{q2}$  in (8), (9), gives

$$\begin{aligned} & -G_{q1}V_{q1}^2 + G_{q1}V_{q1}V_i\cos(\vartheta_{q1} - \vartheta_i) + B_{q1}V_{q1}V_i\sin(\vartheta_{q1} - \vartheta_i) + \\ & -G_{q2}V_{q2}^2 + G_{q2}V_{q2}V_j\cos(\vartheta_{q2} - \vartheta_j) + B_{q2}V_{q2}V_j\sin(\vartheta_{q2} - \vartheta_j) + \\ & + P_{DC} = 0 \end{aligned} \quad (19)$$

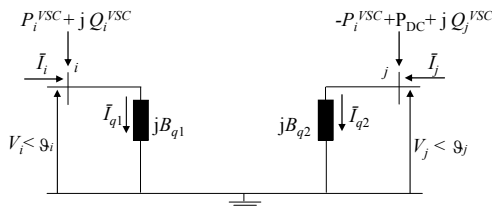
It can be shown that (19) is equivalent to

$$P_i^{VSC} + P_j^{VSC} - P_{DC} = 0 \quad (20)$$

by assuming

$$G_{q1} = G_{q2} = 0 \quad (21)$$

The relation (21) means that the impedances of the two coupling transformers are reactive (resistances neglected). Then, by (15)-(18) and the DC power equality constraint in a diverse form (20), a Power Injection Model (PIM) of VSC-HVDC has been built and demonstrated to be a steady-state model equivalent to the VSM under the necessary assumption (21). Figure 3 shows the PIM equivalent scheme of VSC-HVDC.



**Figure 3:** The Power Injection Model (PIM) of VSC-HVDC.

As it can be seen, in this case the presence of the two voltage sources has been bypassed and their effects are taken into account by the VSC-HVDC power injections at the two nodes. These power injections represent the

controllable variables. This model can be then inserted into a Newton-Raphson load flow algorithm. The PIM offers the same advantages as the VSM, but it also presents a resulting symmetric admittance matrix: it is then a more robust and feasible alternative to the VSM for the VSC-HVDC load flow implementation. These features of PIM may lead to a higher load flow convergence speed, particularly useful for large-scale network simulations. The PIM can be also extended to the case of multiterminal VSC-HVDC, as the VSM has been considered for multiterminal VSC-HVDC in [6]. In case of back-to-back VSC-HVDC with converter losses neglected, or in case of full VSC-HVDC with all DC losses neglected, the model takes account of the equality constraint

$$P_i^{VSC} + P_j^{VSC} = 0 \quad (22)$$

that is, the model is a PIM with null  $P_{DC}$ . This model can be also further simplified for DC network implementations. In DC load flow, the VSC-HVDC can be represented by a decoupled model with the nodal real power injections taking account of the target power flow.

## 4 SUSTAINABILITY OF VSC-HVDC

### 4.1 Environmental aspects

The main environmental benefits of VSC-HVDC, when compared to classic AC, are mostly similar to those of the HVDC technology [3]-[5].

*Land use of lines.* An overhead HVDC line requires less territory than an overhead HVAC line, and even more, an HVDC underground cable occupies significantly less land than an overhead HVDC line. Replacing existing OHLs with DC cables is an opportunity to make valuable land available for other uses.

*Land use of stations.* Converter stations for traditional HVDC systems require more space than a conventional AC substation for the same transmission capability. This is not the case for VSC-HVDC, thanks to the compact and environmentally friendly design.

*Electro-Magnetic Fields (EMFs).* An HVDC installation generates no oscillating low frequency field. The HVDC fields are, contrary to AC lines, static.

### 4.2 Economics of VSC-HVDC

According to [9], technological developments have tended to push HVDC system costs downward, while the environmental considerations have resulted in pushing up the HVAC system costs.

The costs of transmission devices are highly dependent on different parameters such as the size of the equipment, the operating voltage and the local environmental characteristics. For this reason, Table 1 shows the average costs (ranges) of some transmission technologies: for single lines and XLPE (Extruded Cross-Linked Polyethylene) cables a rated capacity between 700 and 1300 MW is considered.

In Table 1 the investment costs of the station components are referred to the throughput power. This has been done also for a FACTS component like the Unified Power Flow Controller (UPFC), having a power rating equal to a fraction (here assumed equal to 0.5) of the line's throughput rating.

The cost of a VSC-HVDC link may be close to the one of an overhead line if all factors are taken into account. For example, the higher costs attached to VSC stations installation and operation should be assessed against the substantial advantages in terms of power flow controllability. In other terms, a VSC-HVDC system should be more properly compared to an HVAC line equipped with fast power flow control devices (like the UPFC).

HVAC and HVDC Transmission lines	Cost	Unit
HVAC overhead single circuit line	200-500	kEUR/km
HVAC overhead double circuit line	300-700	kEUR/km
HVDC overhead bipolar line	200-400	kEUR/km
HVDC XLPE underground cable	1000-2500	kEUR/km
HVDC Converter stations and FACTS	Cost	Unit
Traditional HVDC converter	40-60	kEUR/MVA
VSC-HVDC converter	50-70	kEUR/MVA
UPFC	50-90	kEUR/MVA

**Table 1:** Average investment costs of transmission technologies (Sources [9]-[12]).

In case the transmission of a higher level of power between two zones is of concern, planning the utilisation of VSC-based HVDC devices may represent a possible solution.

The following advantages - deriving from the insertion of VSC-HVDC devices in the grid - are in the present analysis converted in economic benefits:

- transmission capacity enhancement, monetized in terms of increased amount of cheaper energy imported by a zone or country with a higher electricity wholesale price;
- relief of congestions.

VSC-HVDC devices offer also other advantages, which are here not translated in economic revenues. These may include: cancellation, postponement or downsizing of other planned investments; electricity loss reduction; relief of more efficient generation units constrained by network bottlenecks; avoidance/reduction of outages; support to reactive power and voltage control; avoidance/reduction of undesired power flows; avoidance/reduction of non supplied energy.

When comparing the costs and benefits of AC and DC transmission systems, the willingness to bear a higher cost to reduce the visual/territorial impact of infrastructures (not always correlated with the reduction of EMF values) should be properly estimated.

Instead of a HVDC line, other solutions may envisage the deployment of conventional components, such as new HVAC lines, mechanically-switched capacitors, tap-changers.

The comparison and prioritisation of alternative solutions (e.g. a conventional component versus a VSC-HVDC) is performed via cost-benefit analyses based on the following indicators:

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

All these four indicators are used to techno-economically assess the insertion of VSC-HVDC in the liberalised European power system [13]. To evaluate the economic benefits stemming from VSC-HVDC deployment, the cash revenues are calculated as savings derived by an increased cheaper energy flow in the importing power system. These revenues can be expressed in this case as

$$CR = h \Delta\lambda \Delta NTC \quad (23)$$

where  $\Delta\lambda$  is the electricity price differential between the importing and the exporting system,  $\Delta NTC$  is the enhancement of transmission capacity available in secure conditions and granted by the VSC-HVDC installation, and  $h$  is the number of yearly operation hours of the link between the two systems. For a simple formulation of the cash revenues  $CR$  as in (23),  $h$  and  $\Delta\lambda$  have been assumed as invariant with respect to the investment. The Net Transfer Capacity (NTC) differs from the Total Transfer Capability (TTC) by a security margin, the Transmission Reliability Margin (TRM) [14][15].

## 5 TEST RESULTS

In this Section the results of various network implementations with VSC-HVDC models are presented. Load flow simulations have been carried out in Matlab®.

### 5.1 VSC-HVDC Modeling: 3-node network test cases

For the first implementations a small network [7] consisting of 3 nodes and 3 lines has been chosen for load flow tests of the VSC-HVDC models. The goal is to compare the results obtained by implementing the PIM with those ones by the VSM presented in [7]. A lossless, back-to-back VSC-HVDC has been inserted into the line A-C with the objective to control power flow towards bus A at 12.11 MW + j 0.2 MVAR and the voltage magnitude at bus C at 1.0 p.u. In this case, an additional node, D, is needed to connect the VSC-HVDC and the device is actually on the line D-C. Utilizing the VSC-HVDC parameters rates ( $\dot{Y}_{q1} = \dot{Y}_{q2} = -j/0.1$  p.u.,  $0.9$  p.u.  $\leq V_{q1} \leq 1.1$  p.u.,  $0.9$  p.u.  $\leq V_{q2} \leq 1.1$  p.u.) as in [7], the load flow results obtained by implementing both the models, VSM and PIM, are identical.

Newton-Raphson load flow convergence has been achieved to a tolerance of  $10^{-12}$ , within the same number of iterations and speed, by both VSM and PIM. Table 2 and Table 3 show the bus voltages and VSC-HVDC variables' values, respectively, obtained by both the VSM and the PIM.

Bus	A	B	C	D
$V$ (p.u.)	1.000	1.000	1.000	1.016
$\vartheta$ (deg.)	4.83	0.0	-1.62	6.34

**Table 2:** Bus complex voltages by VSM and PIM.

By the PIM the VSC-HVDC real and reactive power injections at nodes D and C result to be equal to 12.11 MW, 1032.0 MVAR, and -12.11 MW, 1016.7 MVAR, respectively. As the results coincide with those ones in [7], the tables confirm the equivalence among the two steady-state models, VSM and PIM, in the lossless case. 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 (shunt)	
$V_{q1}$ (p.u.)	$\vartheta_{q1}$ (deg.)	$P_{q1}$ (MW)	$Q_{q1}$ (MVAR)
1.016	7.01	12.11	0.34
$V_{q2}$ (p.u.)	$\vartheta_{q2}$ (deg.)	$P_{q2}$ (MW)	$Q_{q2}$ (MVAR)
1.017	-2.29	-12.11	17.12

**Table 3:** VSCs variables' values by VSM and PIM.

In the same 3-node network as in [7], a full VSC-HVDC link is now considered between nodes A and C, with a fixed  $V_{DC1}$  and  $R_{DC}$  set at 0.08 p.u. The VSC-HVDC parameters and control targets are the same as in the previous case. The load flow results obtained by PIM equal those ones by VSM, with the same convergence speed and number of iterations. This confirms the validity and properties of PIM also for full VSC-HVDC.

### 5.2 VSC-HVDC Modeling: IEEE 118-bus network

The effects of the insertion of VSC-HVDC in the IEEE 118-bus system [16] are here shown along with the results by the two models.

A lossless, back-to-back VSC-HVDC (having  $\dot{Y}_{q1} = \dot{Y}_{q2} = -j/0.1$  p.u.,  $0.9$  p.u.  $\leq V_{q1} \leq 1.1$  p.u.,  $0.9$  p.u.  $\leq V_{q2} \leq 1.1$  p.u.) has been located into the line between the nodes 95 and 96: the scope is to maintain active and reactive power flows, leaving the VSC-HVDC towards bus 96, at 40 MW and 20 MVAR, respectively, and to control voltage magnitude at node 95 at 1.0 p.u. The VSC-HVDC is then actually placed between node 95 and the additional node, 119. Newton-Raphson load flow convergence has been reached (tolerance of  $10^{-12}$ ) by VSM and PIM implementations; the VSC-HVDC targets have been achieved and the results confirm the equivalence of the two models (active losses neglected). Table 4 shows the VSC-HVDC effects in the IEEE 118-bus system. The greater robust-

ness and feasibility offered by PIM lead to better convergence speed performances by the PIM respect to those ones by VSM.

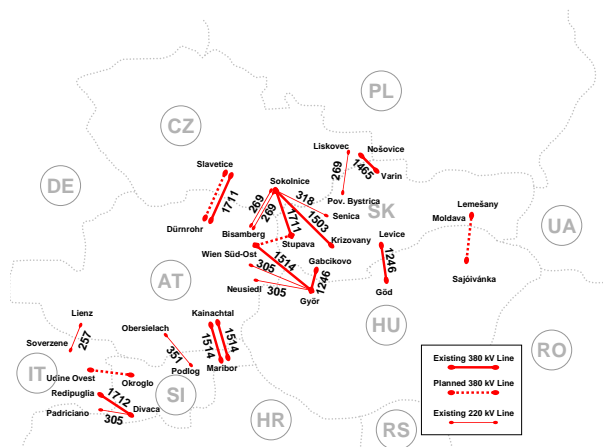
	Without VSC-HVDC	With VSC-HVDC
Mag. Voltage bus 95	0.980 p.u.	1.000 p.u.
Power flows 95-96	-1.38 MW -j21.69 MVAR	-
Power flows 119-96	-	40.0 MW +j 20.0 MVAR

**Table 4:** VSC-HVDC effects in the IEEE 118-bus system.

### 5.3 VSC-HVDC in the European transmission system

A techno-economic assessment of the insertion of VSC-HVDC devices to locally enhance the transmission capacity in the European power system is here presented. This analysis is based on load flow implementation results, which have been then utilised for the calculation of the economic indicators (seen in Section 4) needed for assessing an investment in VSC-HVDC.

Reference system is the 400-220 kV European transmission grid. The test network, to be run for DC load flow studies, is the one described in [17], which gives a good approximation of the real Continental Europe (former UCTE) network (as of 16 Jan. 2002, at 11h00, in winter peak situation), particularly for cross-border flows. This system complemented by and updated with most recent data for the line capacity limits available from [14], consists of 1254 buses, 378 generators and 1944 lines [13]. Attention has been paid especially to the regional power transmission system and cross-border ties of Central-East Europe (comprising the networks of Germany, Austria, Poland, Czech Rep., Slovakia, Hungary and Slovenia) [18]. In particular, focus is on the links of Czech Republic (CZ), Slovakia (SK), Austria (AT) and Hungary (HU), where more network corridors are very frequently congested [14][15]. Figure 4 depicts a schematic representation of this part of the test network with the respective cross-border capacity limits (as of 2007) [13]. A TRM of 200 MW has been considered for the examined cases. Tests simulating the implementation of a lossless VSC-HVDC replacing different HVAC lines in the system have been carried out in a DC load flow network representation. In the base case (without VSC-HVDC) DC load flow analysis on the test network points out bottlenecks at the border between CZ and AT.



**Figure 4:** Cross-border tie lines in Central Europe (2007).

In this case, in fact, the cross-border interconnection lines, Slavetice-Dürnröhr and the 2x220 kV Sokolnice-Bisamberg (see Figure 4), transport 635 MW and 250 MW, respectively, which result in a total 885 MW: this value corresponds to the TTC on the CZ-AT tie (since the (n-1)-criterion is met). However, the difference between TTC and TRM exceeds the total secure power transit, the Net Transfer Capacity (NTC), set at 600 MW on the CZ-AT interface [11]. In this condition a VSC-HVDC device may increase the transferred power from CZ to AT by relieving congestions and exploit the cross-border trade. The utilised VSC-HVDC device has 600 MW as power rating. To solve the above issue, the VSC-HVDC replaces selected cross-border tie lines such as Sokolnice-Bisamberg (line 1). In this respect, the key parameter for the analysis of investment is the increase of NTC represented by  $\Delta NTC$ . The results of these DC load flow studies, taking account of a (n-1) contingency analysis, indicate a  $\Delta NTC$  of 250 MW (calculated according to the rules in [15]), proving the positive contribution of VSC-HVDC to the cross-border capacity increase on the interface CZ-AT.

In addition to the enhancement of transmission capacity by VSC-HVDC and the consequent reduction in congestion occurrence at the cross-border interfaces, the electricity price differential between the importing and exporting systems remains a key element for an investment in VSC-HVDC devices. In this regional power system, the average electricity market price differential between the Austrian and Czech system ( $\Delta\lambda_{AT-CZ}$ ) might also reach 10 €/MWh [18][19]. In order to assess the investment in this VSC-HVDC option at CZ-AT interface, the economic indicators seen in Section 4 have to be calculated. To do this, starting time reference is year 2008 with a timeframe of 25 years. It is assumed that the considered situation in terms of load and generation (connected to the transmission network) in the Central-East Europe system will be kept over the years of observation. The capital expenditure is considered to be 60 k€/MVA for every VSC-HVDC converter, adding 1% of the initial investment for annual maintenance [9]-[12]. Two scenarios for the price differential  $\Delta\lambda_{AT-CZ}$

have been analysed, assuming conservative values of 5 €/MWh (lower price differential scenario) and 7 €/MWh (higher price differential scenario). Considering an interest rate of 10%, it is possible to derive the results shown in Table 5.

$\Delta\lambda_{AT-CZ}$	NPV	IRR	PI	PBP
5 €/MWh	16.3 M€	13%	1.25	13 years
7 €/MWh	49 M€	20%	1.74	7 years

**Table 5:** Economic results for VSC-HVDC on CZ-AT tie.

These results prove the techno-economic feasibility of an investment in VSC-HVDC replacing existing HVAC line(s), especially in presence of regions with a high electricity price differential.

To solve transmission congestion issues, an option such as the building of a new HVAC line is generally considered. This is the case of the cross-border interface between SK and HU, with a new HVAC line from the substation of Moldava (SK) to the node of Sajóvívanka (HU) (see Figure 4). This new link has been already planned but still local problems (social opposition, environmental constraints) hinder this project [20]. A VSC-HVDC link might be a feasible option to bypass these issues and would need much less space and shorter lead time than that required for a new HVAC line. In order to compare the two options the economic indicators indicated in Section 4 have to be calculated under the same assumptions seen in the case of VSC-HVDC on the CZ-AT tie.

An average electricity price differential between HU and SK,  $\Delta\lambda_{HU-SK}$ , has been estimated to be 2 €/MWh (conservative assumption) [18][19]. The capital expenditure is considered to be 400 k€/km for a new 380 kV transmission line and 250 k€/km for an overhead HVDC link, adding 1% of the initial investment for annual maintenance [9]-[12]. Considering that in this case a VSC-HVDC rating of 1100 MW would be needed to provide a  $\Delta NTC$  comparable to that one offered by the new line, it is possible to derive the results shown in Table 6. The case # 1 represents the building of the new HVAC line while case # 2 is the alternative given by a VSC-HVDC link on the SK-HU tie.

Case #	IRR	PI
1	17%	1.5
2	8%	< 1.00

**Table 6:** Results of the investment analyses.

Comparing the results in Table 6, there is the outcome that at the border between Slovakia and Hungary, building the new HVAC line is more economically favourable than installing a VSC-HVDC. In this case a higher VSC-HVDC rating would be necessary to expand more largely the NTC and have a more feasible alternative. This naturally depends also on the specific situation and the issues to be solved in the transmission system at internal level. It has however to be remarked that in this analysis several benefits associated with VSC-HVDC utilisation, such as loss reduction, voltage

support, reactive power control, have not been addressed. Although in the latter case building a new HVAC line results to be more economically convenient, the installation of VSC-HVDC can offer a more feasible option where several constraints (socio-political, environmental) hinder the extension of the HVAC transmission system.

## 6 CONCLUSION

The replacement of existing and/or planned HVAC lines with HVDC infrastructure is an option to transmit larger amounts of power over long distances. Particularly, VSC-HVDC offers important advantages (such as compactness of stations, controllability of power and voltages, possibility for multiterminal operation) and can be then an alternative to conventional HVAC transmission in many situations.

The present paper focuses on the enhancement of transmission capacity by utilising VSC-HVDC. Particular attention has been paid to the technical as well as to the economic and environmental features of such devices. An original model (a Power Injection Model) for VSC-HVDC has been introduced for carrying out AC load flow studies. Tests confirm the validity and the robustness of this model.

Practical DC implementations show the techno-economic feasibility of some targeted VSC-HVDC installations in the European power system when they are replacing existing HVAC lines. This particularly occurs for VSC-HVDCs installed on lines between regions with a high electricity price differential. On the other hand, the deployment of these devices results to be less profitable than building new HVAC lines. However, in this analysis several benefits offered by VSC-HVDC have not been quantitatively addressed. Also, VSC-HVDC can offer a more feasible option where several constraints (socio-political, environmental) impede the extension of the HVAC transmission system. Future work may be focused on a full AC analysis at European level with consideration of other benefits from VSC-HVDC.

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'The views expressed in this paper are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission.'

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