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Sustainability analysis of VSC-HVDC in the liberalised European power system: a practical case

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Abstract-- **The present paper aims at investigating the impact of the emerging Voltage Source Converter-based High Voltage Direct Current (VSC-HVDC) technology on the liberalised power system in Europe. In particular, focus is on key technical, economic, and environmental features of VSC-HVDC. A techno-economic analysis on a European priority interconnection project (i.e. the planned tie line Poland-Lithuania) is undertaken, so as to compare the economic and environmental sustainability of an investment in VSC-HVDC with other options.**

Index Terms-- **Analysis of investments, European power system liberalisation, VSC-HVDC, power flow analysis, steady state modeling, transmission planning.**

I. Introduction

The transmission network planning and development processes have recently come to the forefront as critical instruments to pursue the European Union's energy policy objectives of competitiveness, sustainability and security of supply. The inheritance by the enlarged European Union (EU) of weak east-west and south-north connections, the aging of electricity infrastructures and the lack of suitable network links for the integration of renewable energy sources may pose obstacles to the cross-border electricity flows and make some regions more vulnerable to supply disruption [1].

Within this background in the EU, the solution of increasing the power transmission capacity, traditionally realized by means of High Voltage Alternating Current (HVAC) infrastructures, is nowadays seriously hampered by economic, environmental, and political constraints. Moreover, a more flexible transmission grid is needed to further integrate renewable generation technologies into the system. Novel solutions are therefore needed to strike a balance between environmental/visual impact abatement and flexible transmission capacity increase. Then, the deployment of High Voltage Direct Current (HVDC) transmission systems may represent a solution displacing conventional HVAC technologies in broader fields of application.

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In fact, HVDC is a well established power electronics-based technology and presents characteristics that have made it widely attractive over HVAC transmission for specific applications such as long-distance power transmission, long submarine cable links and interconnection of asynchronous systems [2][3]. Conventional (thyristor-based) HVDC transmission using line commutated conversion is mostly based on CSC (Current Source Converter) [3].

Currently, recent advances in power electronics may lead to further deployment of HVDC technology towards improving the operation and sustaining the development of the European transmission grid. Indeed, the application of VSC (Voltage Source Converter)-based HVDC can provide the European power system with generally enhanced system security and controllability.

The latter properties are especially important in a deregulated environment, where VSC-HVDC can be an attractive option to efficiently and timely relieve network constraints, thus reducing the need for building new HVAC lines [3][4]. Moreover, concerning the environmental impact, VSC-HVDC may offer a smaller territorial footprint respect to HVAC lines. However, accurate cost-benefit analyses need to be carried out in order to better understand the impact that HVDC technologies may have on the power system.

The present paper, focusing on key technical, economic, and environmental features, aims at investigating the sustainability of an investment in VSC-HVDC, also compared to other options, in the European power system. Towards this scope, specific attention is paid to the transmission capacity enhancement as well as to surface occupation reduction attainable by VSC-HVDC. Based on DC load flow studies, a techno-economic assessment of the impact of VSC-HVDC on targeted applications in the liberalized power system in Europe is finally undertaken.

In this paper, Section II. focuses on VSC-HVDC modeling suitable for DC load flow studies. Section III. highlights the main VSC-HVDC economic and environmental features. Section IV. introduces the investment analysis. Section V. presents the results of practical test cases towards a cost-benefit assessment of the effects of VSC-HVDC in the European power system. Focus is particularly on one of the key European electricity projects [5], namely the Poland-Lithuania interconnection link.

II. VSC-HVDC Modeling for Load Flow Studies

The properties and characteristics of VSC (Voltage Source Converter)-based HVDC have been recently investigated and described in open literature ([3][4][9][10] 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 technology offers compact and modular converter stations and the possibility for an easier expansibility to multiterminal configurations [4].

Fig. 1 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 transformation), while VSC 2 behaves as an inverter (DC-AC transformation). The DC circuit links the two converters and can be made by line(s) or cable(s) (full VSC-HVDC, as schematized in Fig. 1, in which R_{DC} represents the resistance of the DC connector, and C_1 and C_2 are the respective capacitors at converters' sides) or simply the storage capacitor C (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. Both converters are capable of independently controlling the amount of reactive power exchanged with the respective AC node, and then independently controlling 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 [9][10]. In Fig. 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.

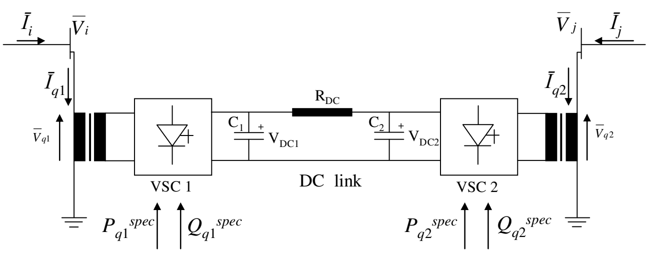

Fig. 1. A basic scheme of full VSC-HVDC.

In order to develop VSC-HVDC modeling for steady-state studies the equivalent representation of a Voltage Source Model (VSM) for VSC-HVDC shown in Fig. 2 has been taken into account [9]-[11].

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, $\overline{V}_{q1}$ and $\overline{V}_{q2}$, 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:

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

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

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

$$\dot{Y}_{q1} = G_{q1} + \mathrm{j}B_{q1} \quad (3)$$

$$\dot{Y}_{q2} = G_{q2} + \mathrm{j}B_{q2} \quad (4)$$

where G_{q1}, B_{q1}, and G_{q2}, B_{q2}, are the coupling conductance and susceptance of VSC 1 and VSC 2, respectively.

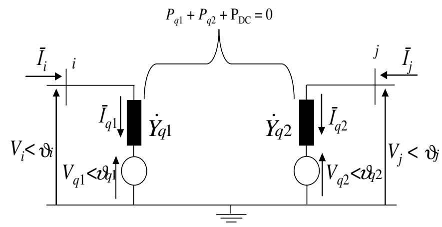

Fig. 2. The Voltage Source Model (VSM) of VSC-HVDC.

From the scheme of VSM (see Fig. 2) and considering (1)-(4), the load flow equations at nodes *i*, *j* can be obtained respectively as

$$P_i = G_{q1}V_i^2 - G_{q1} V_i V_{q1} \cos(\vartheta_i - \vartheta_{q1}) - B_{q1} V_i V_{q1} \sin(\vartheta_i - \vartheta_{q1}) \quad (5)$$

$$Q_i = -B_{q1}V_i^2 - G_{q1} V_i V_{q1} \sin(\vartheta_i - \vartheta_{q1}) + B_{q1} V_i V_{q1} \cos(\vartheta_i - \vartheta_{q1}) \quad (6)$$

$$P_j = G_{q2}V_j^2 - G_{q2} V_j V_{q2} \cos(\vartheta_j - \vartheta_{q2}) - B_{q2} V_j V_{q2} \sin(\vartheta_j - \vartheta_{q2}) \quad (7)$$

$$Q_j = -B_{q2}V_j^2 - G_{q2} V_j V_{q2} \sin(\vartheta_j - \vartheta_{q2}) + B_{q2} V_j V_{q2} \cos(\vartheta_j - \vartheta_{q2}) \quad (8)$$

Also, the active and reactive powers absorbed respectively by VSC 1 and VSC 2 can be calculated as

$$P_{q1} = -G_{q1}V_{q1}^2 + G_{q1} V_{q1} V_i \cos(\vartheta_{q1} - \vartheta_i) + B_{q1}V_{q1}V_i \sin(\vartheta_{q1} - \vartheta_i) \quad (9)$$

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

$$P_{q2} = -G_{q2}V_{q2}^2 + G_{q2} V_{q2} V_j \cos(\vartheta_{q2} - \vartheta_j) + B_{q2} V_{q2} V_j \sin(\vartheta_{q2} - \vartheta_j) \quad (11)$$

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

To maintain the DC power balance, the active power flowing from the sending bus (for instance, node *i*) has to be equal with 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:

$P_{q1} + P_{q2} + P_{DC} = 0$ (13)

where P_{q1}, P_{q2} are expressed as in (9), (10) and P_{DC} represents the DC side power losses, respectively. Equation (13) is a necessary equality constraint to be considered in the VSM of VSC-HVDC.

By the assumption that the DC link voltages at capacitors C_1 and C_2, V_{DC1} and V_{DC2} (see also Fig. 1), are kept practically fixed by the operation of the two converters, the DC power losses can be considered constant, when neglecting the converters losses. In this case, the term P_{DC} results to be

$P_{DC} = (V_{DC1} - V_{DC2})^2 / R_{DC}$ (14)

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

$P_{DC} = 0$ (15)

The same result as in (15) is also the case for a full VSC-HVDC scheme when neglecting all DC losses.

This model can be then inserted into a Newton-Raphson load flow algorithm [10].

Considering now 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 under the above assumptions. In this case in fact the VSC-HVDC can be modeled by means of a load and a generator, as Fig. 3 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. The term of P_{DC} can be represented by one of the expressions in (14)-(15), depending on the chosen VSC-HVDC configuration and assumptions. This decoupled model for VSC-HVDC can be inserted in standard Newton-Raphson load flow algorithms. After load flow convergence, the VSC-HVDC parameters V_{q1}, ϑ_{q1}, V_{q2}, ϑ_{q2} can be computed by solving the set of equations (5)-(8).

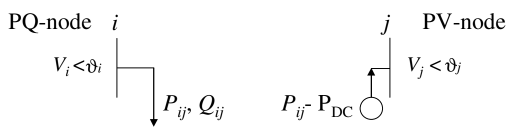

Fig. 3. The decoupled model of VSC-HVDC.

This decoupled model can be also be considered for DC studies: in these cases, being reactive power absent, focus is on real power flow control with nodal voltage amplitudes fixed at 1 p.u. and DC side losses constant.

III. Sustainability of Investments in VSC-HVDC

A. Economics of VSC-HVDC

Capital expenditures for transmission lines are highly dependent on different parameters such as the equipment rating, the operating voltage, the local environmental characteristics and material/manpower costs. In general, environmental constraints increase costs and implementation time for overhead lines (OHL), whilst technological advances significantly reduce costs of underground transmission via e.g. Extruded Cross Linked Polyethylene (XLPE) technology [12]. It has also to be stressed that to date the projects already implemented deploying VSC-HDVC technologies refer to power ratings generally lower than the ones used in this study. Furthermore, stakeholders and manufacturers are still reluctant to provide relevant cost figures. In order to take into account all these factors, Table I reports ranges for the costs of different 400 kV transmission components, based on data in [6]-[8],[11][12]. Costs ranges are reported to compare HVAC technologies (for a throughput power of 1300 MVA) and HVDC devices (for a throughput power of 1000 MW). The investment in a VSC-HVDC link, which is generally bipolar, may be comparable to the investment in a HVAC system if more factors are taken into account. For instance, 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 a fast power flow control device, like a FACTS.

TABLE I
Transmission Components Cost Data

Cost of components	Rating	Min	Max	Unit
HVAC OHL single circuit		200	500	kEUR/km
HVAC OHL double circuit	1300 MVA	400	800	kEUR/km
HVAC underground XLPE cable		1000	3000	kEUR/km
reactive compensation		150	150	kEUR/km
HVDC OHL bipolar		200	400	kEUR/km
HVDC underground XLPE cable (pair)	1000 MW	1000	2500	kEUR/km
VSC Converter		50000	80000	kEUR
CSC Converter		40000	70000	kEUR
operation + compensations (% installation costs)		10	20	%

B. Environmental aspects

The main environmental benefits of VSC-HVDC, when compared to classic HVAC transmission, are similar to those ones of the HVDC technology [3][11][13].

Electro-Magnetic Fields (EMFs). HVDC installations, contrary to AC lines, generate no oscillating low frequency field but only static fields. Moreover, the magnetic field generated by a pair of HVDC cables in typical installation conditions is generally lower than the earth magnetic field.

Surface occupation of lines. An overhead HVDC line requires less territory than an overhead HVAC line with equivalent carrying capacity, and even more, an HVDC underground cable occupies significantly less land than an overhead HVDC line. Replacing existing OHLs with DC cables may be evaluated in terms of land made available and monetized in terms of earnings related to other uses of such land. AC underground cables generally need less right-of-way than AC overhead lines as well, but they are suitable to cover shorter distances, unless the use of compensation reactors to cope with the increased reactive and short circuit power is envisaged, with consequent higher costs.

Surface occupation 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: due to its more compact design, a VSC requires much less space than a CSC.

Table II displays ranges for the occupation of territory, since the right-of-ways depend on several features (e.g. line configuration, EMF national/regional legislation) and in this study are mostly extrapolated from [12][13].

TABLE II
SURFACE OCCUPATION DATA

Land use	Rating	Min	Max	Unit
HVAC OHL single circuit	1300 MVA	40000	60000	m2/km
HVAC OHL double circuit		60000	70000	m2/km
HVAC underground XLPE cable		5000	15000	m2/km
reactive compensation unit		2000	3000	m2
HVDC OHL bipolar	1000 MW	20000	40000	m2/km
HVDC underground XLPE cable		5000	10000	m2/km
VSC Converter		5000	10000	m2
CSC Converter		10000	30000	m2

IV. INVESTMENT ANALYSIS

In case the transmission of a higher level of power between two zones is of concern, a solution may be the deployment of VSC-based HVDC instead of conventional transmission technologies. Depending on the network features (e.g. adequacy and topology), a new link may offer also the possibility to increasingly exploit more efficient and/or renewable source-based electricity generation spread in the system. This additional capacity can then replace the electricity capacity of less efficient generation (substitution effect) leading to a system CO_2 emission reduction. VSC-HVDC can be also used to interconnect asynchronous systems or areas.

The following advantages are quantified in the present analysis:

- Transmission capacity enhancement, monetized in terms of increased cheaper energy imported by a zone or country with a higher electricity wholesale price;
- Emissions reduction, as a consequence of the exploitation of more efficient (in particular renewable) electricity generation capacity, quantified in terms of CO_2 emissions avoided and monetized in terms of carbon tax savings;
- Surface occupation, evaluated in terms of km^2 of land devoted to plants' right-of ways;
- Additional energy exchange secured by fast power flow control 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 VSC-HVDC links since they can quickly react to steer and control rapid power flow variations also brought about by renewable electricity sources (like wind e.g.).

VSC-HVDC systems offer also other advantages, here not quantified, such as: punctual support to reactive power and voltage control; avoidance/reduction of undesired power flows; EMFs abatement. Additional benefits, here not monetized, that a network reinforcement may produce are: cancellation, postponement or downsizing of other planned investments; electricity loss reduction; relief of congestions; relief of more efficient generation units constrained by network bottlenecks; reduction of energy not supplied after outages; reduction of the amount of generation reserve.

In general, a project requires an initial investment, which is then gradually recovered by means of the earnings coming from the implemented project. The future revenues have to be discounted according to the expected accumulated inflation and interest rates. In this analysis a fundamental concept is given by the operating cash flow, represented by the revenues generated from operations subtracting the direct and indirect costs, expenses for taxation and interests, investment incomes and dividends paid.

Instead of using VSC-HVDC technologies, other solutions may envisage the deployment of conventional components, in particular new HVAC lines, equipped or not with fast power flow control devices (FACTS).

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

These four indicators are used to techno-economically assess and compare the insertion of VSC-HVDC respect to other traditional solutions in the liberalized European power system. Among the economic benefits stemming from an interconnection project there are the cash revenues calculated as savings derived by an increased cheaper energy flow in the importing power system. These revenues can be expressed in this case as

$$CR = h \ \Delta\lambda \ \Delta NTC \tag{16}$$

where $\Delta\lambda$ is the electricity price differential between the importing and the exporting system, ΔNTC is the enhancement of transmission capacity available in secure conditions and granted by the new link installation, and h represents the yearly utilization hours of that link providing ΔNTC. 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 account of 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) [15][16].

V. TEST RESULTS: THE POLAND-LITHUANIA LINK

This Section investigates the techno-economic and environmental sustainability of building a VSC-HVDC link as an alternative to other conventional technologies, in order to increase the transmission capacity in the liberalized European power system. A VSC-HVDC link, modeled for DC load flow studies as seen in Section II., has been inserted in the test network. Simulations have been run in Matlab® to assess the NTC increase granted by a new interconnection line built between two power systems. The results have been then utilized for the calculation of the economic indicators (seen in Section IV.) to compare viability and degree of profitability of the selected options based upon HVAC and HVDC technologies. Reference system is the European transmission grid and the test network (at 400-220 kV) is the one described in [14] suitable for DC studies: it consists of 1254 buses, 378 generators and 1944 lines and conveniently approximates the UCTE (continental Europe) network, especially concerning the cross-border flows. For this system the line capacity limits have been updated with data available from [15]. In addition to this UCTE network, a part of the interconnected Russian IPS/UPS system, namely the one of the Baltic States Lithuania, Latvia and Estonia (BALTSO system), has been taken in consideration (see Fig. 4) [17]. This system, which is operated at 330-220 kV, consists of a total of 37 buses, 17 generators and 64 lines (including the interconnections with the other IPS/UPS countries such as Russia and Belarus and with Finland via submarine VSC-HVDC link). An equivalent network suitable for DC studies, based on publicly available data [15]-[17], has been utilized for this BALTSO grid.

Fig. 4. Map of the BALTSO system.

The UCTE and the BALTSO systems are currently neither synchronously nor asynchronously directly interconnected. Focus of this paper is in particular on Poland (PL), whose transmission network belongs to UCTE, and Lithuania (LT) (see Fig. 5). These are the only two geographically bordering countries in the EU whose power systems are not interconnected via an electricity link. In order to bridge this gap and close the Baltic Energy Ring between the Lithuanian, Latvian, Estonian, Finnish, Swedish and Polish power systems, a PL-LT link is then crucial. This will help ensure the operation security and reliability of Baltic power grids, their integration into the common European power market as well as the exploitation of local renewable electricity sources (wind). These aspects are expected to play a primary role also taking into account that the Ignalina nuclear plant, located in Lithuania, will be phased out at the end of 2009 and a final decision on a new nuclear plant is yet to come. In addition, a PL-LT link will help secure power supply for Poland's north-eastern region [18][21].

For all these reasons, the PL-LT electricity interconnection is a priority project (EL.7 European interest project) in the frame of EU's Trans-European Energy Networks [5][19]: this project, also known as LitPol link, foresees the interconnection of the PL-LT networks via new land transmission lines [20][21]. Future interconnections in the region will be the projected HVDC undersea cables from Finland to Estonia (a new one) and from Sweden to Lithuania and/or Latvia [17].

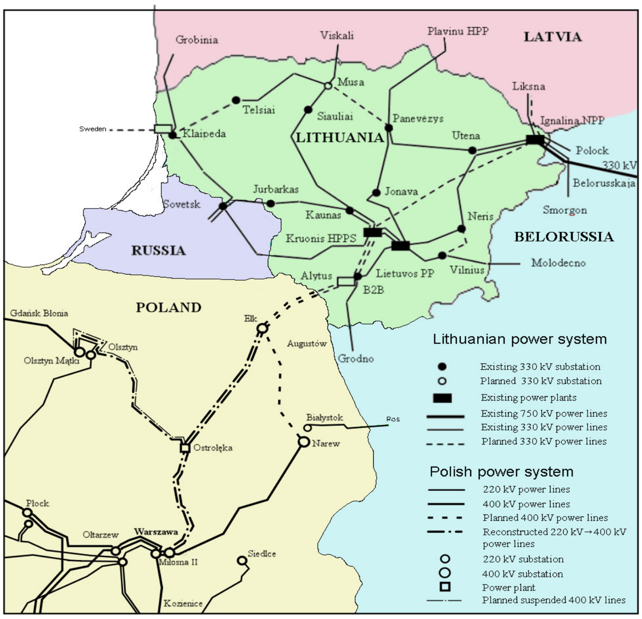

Fig. 5. Transmission networks at the PL-LT border [18].

Preliminary evaluation studies [17][22][23] on the PL-LT case have shown that a new 154-km long interconnection line shall link the existing substations of Ełk (PL) and Alytus (LT) (Fig. 5). Also, this interconnection, under the presently given conditions, shall be asynchronous, either via HVAC link with a back-to-back substation in Alytus or via HVDC technology.

In order to fully exploit the new cross-border line, it is also necessary to reinforce both Lithuanian and Polish internal power grids [20][21]. In particular, on the Polish side the required reinforcements are: the upgrade of Ełk and Ostrołęka substations; the construction of new 400 kV lines (such as the single circuit line Ełk – Narew and the double circuit lines Ostrołęka – Olsztyn Mątki, Ostrołęka – Ełk, and Miłosna – Ostrołęka). In the Lithuanian internal grid different network upgrades at 330 kV are scheduled like: the reconstruction and extension of Alytus and Kruonis substations; the construction of the double circuit line Kruonis – Alytus; the extension of Ignalina switchyard; the construction of the single circuit line Kruonis – Ignalina. The latter works concerning Ignalina substation/line are however much dependent on the commissioning of the new nuclear reactor there located. According to recent estimations, the total investment costs for the internal grids reinforcements amount to 466 M€ ca. (371 M€ in Poland, 95 M€ in Lithuania) [18]-[21].

Scope of the analysis here is to evaluate and compare the options related to the new interconnection link between Ełk and Alytus from the techno-economic and environmental point of view. For the techno-economic assessment DC load flow analyses have been performed to calculate the NTC values. The ETSO method [24] has been adopted to compute the interconnection transfer capacity. The Transmission Reliability Margin (TRM) has been set at 200 MW for the PL-LT interconnection.

For the environmental assessment it has to be remarked that a large part of the new interconnection line corridor would cross an environmentally protected natural area [19][21]. In this context, emerging technologies such as the VSC-HVDC, for the environmental features and advantages as described in III.B, have to be duly taken into account. For this reason, by considering the new cross-border tie with the aim to interconnect the two bordering systems and establish a NTC, four alternative options have been devised and compared in this work by connecting the Ełk and Alytus substations. These four options using either a double HVAC circuit with a rated power of 1300 MVA or a HVDC link with 1000 MW rated power are:

Option 1: HVAC OHL + back-to-back
Option 2: HVDC underground cable
Option 3: VSC-HVDC OHL
Option 4: VSC-HVDC underground cable

Option 1 and Option 2 represent conventional solutions, while Option 3 and Option 4 are advanced solutions. Further DC load flow analyses have resulted in a ΔNTC level of 1000 MW granted by the new 400 kV PL-LT tie. It has been assumed that the considered situation in terms of load and generation is kept over the years of observation. The 400 kV reinforcements planned in the Polish and in the Lithuanian networks have been implemented in the equivalent network model. For the calculation of the NTC level, contingency analyses by the (n-1)-security criterion have been carried out on the cross-border ties. A VSC-HVDC link has been utilized for DC studies as modeled in Section II. The VSC-HVDC control has been supposed to keep V_{DC1} and V_{DC2} respectively at 98% and 100% of their nominal values. The parameters used for the HVAC and HVDC lines and cables are those ones as in [25]. The total investment costs needed for the four different options are expressed in ranges between minimum and maximum values, based upon the elementary cost displayed in Table I. The investment costs are distinguished in capital expenditures and in operation and environmental compensation expenditures. With reference to the operation and environmental costs, they have been supposed to span from 10 to 20% of the construction costs. They may include rationalization works on lower voltage level networks and other local compensations.

In order to compare the different possibilities (Option 1 vs. Option 3 and Option 2 vs. Option 4), a techno-economic assessment is first carried out by using the results of the aforementioned cases and evaluating the economic indicators described in Section IV. In addition to the enhancement of transmission capacity by VSC-HVDC, the electricity price differential, $\Delta\lambda$, between the importing and exporting systems remains a key element for an investment in VSC-HVDC devices. A parametric evaluation has been conducted to assess the minimum price differentials needed to make the different investment options profitable. It has been assumed that the new interconnector guarantees an energy exchange at the given differential price, equivalent to the ΔNTC value available for 7000 yearly hours over the observation period (20 years starting from 2012). An interest rate of 10 % has been considered.

Moreover, based on evaluations of [26], it has been considered that the new PL-LT link may grant the installation and operation of additional wind generation capacity in the Baltic regions (particularly wind offshore to be eventually connected to the node of Klaipeda in Lithuania). Thus, wind power may replace conventional thermal power for generating electricity, resulting in a carbon emissions reduction. This benefit can be evaluated over the years of observation by conservatively assuming an additional 300 MW wind capacity operating for 3500 yearly hours and replacing Polish coal-based generation assumed emitting an average 1.0 t CO_2/MWh; the carbon tax is set at 20 €/t CO_2. In general, the link would serve for prevalently exporting power from Poland to Lithuania (and the other Baltic countries and Finland) in the first years of observation (2012-2020). Instead, the reversal situation might occur from 2020 onwards due to expected stronger environmental constraints on Polish coal-based generation and installation of the new nuclear power plant in Lithuania.

Also, a VSC-HVDC link can offer an increased amount of exchanged energy. In fact, this VSC-HVDC technology is able to make available an additional quota of electricity produced by variable renewable sources, quickly reacting to rapid generation variations (by wind and hydro power generation).

This controllability benefit is achievable by the Option 3 and Option 4. The increased energy exchanged through the VSC-HVDC link is assessed to amount to 700 GWh per year (corresponding to a further 200 MW cross-border capacity).

Comparing the results in Figs. 6-7, within the assumed conditions and the considered benefits, Option 3 results the most profitable, while among the solutions resorting to undergrounding Option 2 results slightly more convenient. The installation of a VSC-HVDC underground cable (Option 4-Min) begins to be profitable already for a low price differential (2 EUR/MWh) recorded over the observation period. However, if less optimistic estimates on the investment costs (Option 4-Max) are taken into account, the price differential that makes the project profitable over the observation period amounts to 8 EUR/MWh. As it can be noticed, the fast power flow controllability features offered by Option 3 and Option 4 can ensure levels of profitability respectively higher and similar respect to those ones offered by Option 1 and Option 2. It has to be remarked that the HVAC solution (Option 1) is here penalized by the utilization of a costly back-to-back station (AC/DC/AC converters) needed for the interconnection of two asynchronously operated systems.

In contrast with [22], under the given conditions and assumptions, the HVDC options have to be then taken in the due account in the planning process of the new PL-LT interconnection link.

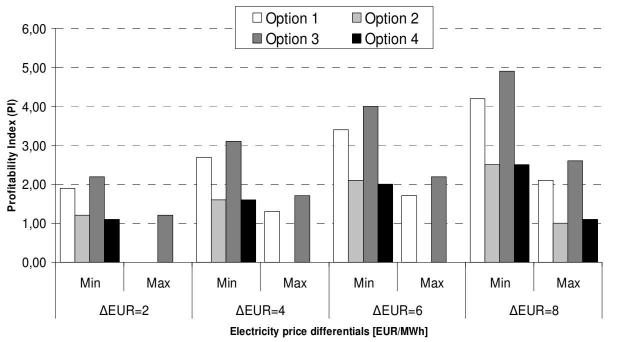

Fig. 6. Profitability index as a function of price differential for the four options.

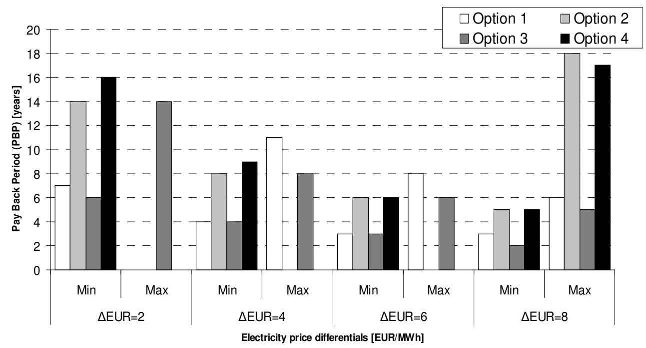

Fig. 7. Pay back period as a function of price differential for the four options.

Moreover, the different options need to be also compared in terms of land use (surface occupation) resulting from the building of the new link. Fig. 8 shows the minimum and the maximum levels of land use needed for the four options, based on the data reported in Table II. It can be noticed that the costlier Option 4 regains some advantages over the other options since it needs on average approximately less than a third and a ninth of the right-of-ways required by Option 1 and Option 3, for instance. A step forward in the surface occupation assessment will require the land value monetization, e.g. according to the land registry values. A further, challenging analysis refinement will then entail the quantification of the economic losses caused by the new installations to activities locally planned and/or carried out (e.g. cables may pose more restrictions than lines upon specific agriculture practices) and of the visual impact of the infrastructures. However, the monetization of these aspects depends on several local elements and is beyond the scope of this paper.

In a selection process typical of network expansion planning procedures, by taking both profitability and land use into account, Option 1 is also penalized due to its higher land use value compared to the remaining options. This leads to choosing an HVDC option under the given conditions and assumptions. Moreover, HVDC options offer the advantage of static-only and generally lower EMFs over HVAC. Depending on the local environmental constraints and protected areas legislation, an HVDC underground solution (Option 2 and Option 4) might then be chosen. Since the outcomes of the techno-economic and environmental assessment provide very similar results for Option 2 and Option 4, the latter solution (VSC-HVDC cable) offering more controllability advantages should then be considered. On the other side, in case of a planning process based on a prevalent techno-economic assessment, Option 3 (VSC-HVDC overhead line) should then be applied for the PL-LT link. It is worth reminding that, being this analysis based on publicly available data and therefore on an approximate DC network model, some further benefits associated with VSC-HVDC operation, such as loss reduction, reactive power and voltage support, cannot be quantified.

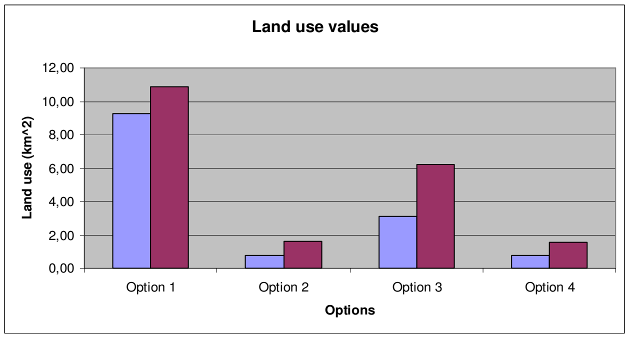

Fig. 8. Land use values for the four options.

It has to be finally remarked that the Polish TSO (PSE-Operator [21]) and the Lithuanian TSO (Lietuvos Energija [18]), under the supervision of the European Coordinator for the PL-LT link, are currently seeking for a solution for the new cross-border line between Ełk and Alytus [19].

In conclusion, this work recognizes quite clearly the advantages, both from the technical and the environmental point of view, offered by VSC-HVDC technology. In cases where environmental/social drivers justify the financing of underground solutions, VSC-HVDC technology represents an attractive option to be taken into account for its flexibility and fast controllability features, in conjunction with HVDC cables.

VI. Conclusion

The present paper focuses on the implications of utilizing VSC-HVDC to enhance the transmission system capacity in a liberalized power system. The VSC-HVDC is first modelled in an original way, for full AC and DC load flow studies, through a decoupled model derived from the Voltage Source Model under opportune assumptions. A techno-economic analysis and a subsequent environmental assessment are carried out to compare investments in VSC-HVDC to other grid reinforcement solutions. Practical DC test cases on a new Poland-Lithuania interconnection show that the VSC-HVDC overhead line option can be more cost-effective than the one based on HVAC overhead line complemented by back-to-back station. In this case, the transmission capacity enhancement, the exploitation of renewable energy sources and the fast controllability features are quantitatively monetized.

However, by considering also environmental and social aspects in the assessment, underground HVDC solutions might be preferred over overhead options. This occurs, in particular, if the ever amplifying environmental sensitivity leads society to accept the higher costs attached to HVDC solutions. Moreover, VSC-HVDC underground installations can be preferred over conventional HVDC underground systems if their higher controllability features are also fully taken into account. From this point of view, VSC-HVDC technology can offer several benefits when coupled with HVDC cables for undergrounding solutions.

Future work may be focused on a further quantification of the technical (by performing a full AC analysis) and environmental features of VSC-HVDC. In sum, provided that all the technical and environmental advantages are monetized, VSC-HVDC technology for overhead and underground solutions may be preferred over the corresponding conventional HVAC and HVDC options.

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