Expansion of Offshore HVDC Grids

An overview of contributions, status, challenges and perspectives

Atousa Elahidoost
Department of Electric Power Engineering
Norwegian University of Science and Technology
Trondheim, Norway
atousa.elahidoost@ntnu.no

Elisabetta Tedeschi
Department of Electric Power Engineering
Norwegian University of Science and Technology
Trondheim, Norway
elisabetta.tedeschi@ntnu.no

***Abstract*—The goal of this paper is to review, systematize and critically discuss the approaches that have been proposed so far for grid transmission expansion in HVDC systems. In particular, the paper will focus on the special planning requirements of *offshore* HVDC grids, which have been seldom addressed by available literature. This contribution will first highlight how traditional expansion planning approaches commonly applied to AC systems need to be modified to properly include the HVDC technology; then it will outline how strategies and tools should be adapted when dealing with large offshore HVDC systems, such as the forthcoming North Sea Offshore Grid. On this respect, an updated overview of existing and planned HVDC links in the North Sea will be provided. Finally, a discussion of the specific challenges that need to be properly addressed by the expansion problem of offshore HVDC networks will be presented, with particular emphasis on renewable energy integration and control issues.**

Keywords*—*HVDC systems; expansion planning; topology optimization; HVDC control; North Sea Offshore Grid; hybrid systems

I. Introduction

The continuous growth in new wind farm installations made wind energy become the second largest form of power generation capacity in Europe in 2016. Out of 53.7 GW of total installed wind capacity at the end of 2016, 12.6 GW (13%) correspond to offshore installations [1]. Such trend, together with the liberalization of energy markets and subsequent increasing need for long-distance and cross-border power transmission, extended the application of High Voltage Direct Current (HVDC) systems. Thanks to their flexible operation, HVDC links avoid grid congestions and allow interconnection of asynchronous areas, as well as subsea transmission to and from offshore sites. In particular, HVDC systems based on the Voltage Source Converter (VSC) technology are the best candidates for the implementation of complex grid topologies, such as multi-terminal and meshed networks, due to their flexibility in control of active and reactive power, and the ability to operate in weak grids and provide black-start services. A VSC-based North Sea Offshore Grid (NSOG) is expected to be deployed in the next decades to enable the full exploitation of offshore wind power in the North Sea, hydro-power with storage capacity in Norway and other renewables in continental Europe. This may be the first step of an ever-growing European "Super-grid" for interconnection of the European countries up to the North African region.

Improved network reliability, security of supply, reduced greenhouse gases (especially CO_2) and lower energy prices owing to liberalization and market competition can be the minimum achievement of the European multi-terminal network. Several scenarios have been presented so far to propose a possible roadmap for development of the future European super-grid. The 2030 timeframe proposed by EWEA [2], the 10-Year Network Development Plan (TYNDP) 2014 by ENTSO-E [3], the powE[R] 2030 by Greenpeace [4], the continental overlay HVDC grid by ABB [5] and the 2050 scenario by Friends of the Super-grid (FOSG) [6] are examples of such scenarios. The focus of all these roadmaps is on the phase out of coal and nuclear power plants and increase of renewable energy penetration. Offshore HVDC grids in North Sea plays a pivotal role in this regard.

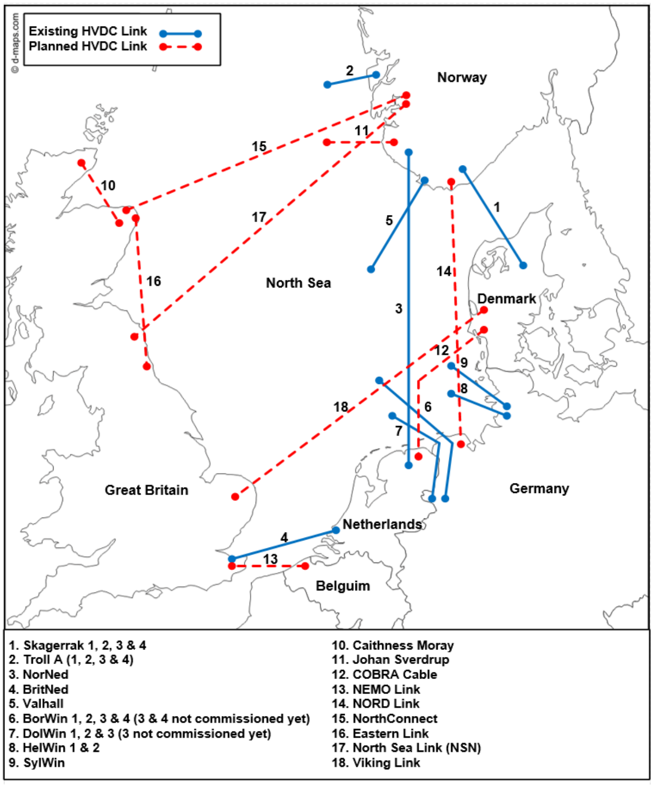

Fig. 1. Existing and planned HVDC interconnections in the North Sea.

TABLE I: THE NORTH SEA HVDC LINKS.

No.	Name	Country	Year of Commissioning	Power (MW)	DC Voltage (kV)	Transmission Length (km)	Converter Type
1	Skagerrak 1&2	Norway - Denmark	1976-7	500	250	113 (OHL), 127 (Submarine),	HVDC Classic
	Skagerrak 3	Norway - Denmark	1993	500	350	113 (OHL), 127 (Submarine),	HVDC Classic
	Skagerrak 4	Norway - Denmark	2014	700	500	104 (Underground), 140 (Submarine)	HVDC Light
2	Troll A (1&2)	Norway	2005	88	±60	4 x 70 (Submarine)	HVDC Light
	Troll A (3&4)	Norway	2015	100	±60	4 x 70 (Submarine)	HVDC Light
3	NorNed	Norway - Netherlands	2008	700	±450	2 x 580 (Submarine)	HVDC Classic
4	BritNed	Netherlands - Great Britain	2011	1000	±450	260 (Submarine)	LCC
5	Valhall	Norway	2011	78	150	292 (Submarine)	HVDC Light
6	BorWin1	Germany	2015	400	±150	2 x 75 (Underground), 2 x 125 (Submarine)	HVDC Light
	BorWin2	Germany	2015	800	±300	75 (Underground), 125 (Submarine)	HVDC PLUS (VSC MMC)
	BorWin3	Germany	2019	900	±320	30 (Underground), 130 (Submarine)	HVDC PLUS (VSC MMC)
	BorWin4	Germany	2020	900	600	2 x 172 (Underground), 2 x 122.4 (Submarine)	N.A.
7	DolWin1	Germany	2015	800	±320	2 x 90 (Underground), 2 x 75 (Submarine)	HVDC Light
	DolWin2	Germany	2016	916	±320	2 x 90 (Underground), 2 x 45 (Submarine)	HVDC Light
	DolWin3	Germany	2017	900	±320	79 (Underground), 83 (Submarine)	N.A.
8	HelWin1	Germany	2015	576	±250	45 (Underground), 85 (Submarine)	HVDC PLUS (VSC MMC)
	HelWin2	Germany	2015	690	±320	45 (Underground), 85 (Submarine)	VSC
9	SylWin1	Germany	2015	864	±320	45 (Underground), 160 (Submarine)	VSC
10	Caithness - Moray	Great Britain	2018	1200	±320	160	HVDC Light
11	Johan Sverdrup	Norway	2019	100	±80	2 x 200 (Submarine)	HVDC Light
12	COBRA Cable	Denmark - Netherland	2019	700	±320	26 (Underground) 299 (Submarine)	VSC
13	NEMO Link	Belgium - Great Britain	2019	1000	±400	10 (Underground), 130 (Submarine)	LCC
14	NORD Link	Norway - Germany	2019	1400	±500	107 (Underground), 516 (Submarine)	HVDC Light
15	NorthConnect	Norway - Great Britain	2020	1400	±500	570 (Submarine)	N.A.
16	Eastern Link	Great Britain	2020	2000	400	305	N.A.
17	North Sea Link (NSN)	Norway - Great Britain	2021	1400	±525	730 (Submarine)	HVDC Light
18	Viking Link	Denmark - Great Britain	2022	1400	400	110 (Underground), 650 (Submarine)	VSC

Abbreviations: OHL: OverHead Line; LCC: Line Commutated Converter; VSC: Voltage Source Converter; MMC: Modular Multilevel Converter; N.A.: Not Available.

II. TRANSMISSION EXPANSION PLANNING IN AC SYSTEMS

As shown in Figure 1, several HVDC systems have been already deployed in the North Sea and several others are in the planning or commissioning phase. As can be inferred from their different voltage and power levels, years of commissioning and technology used (Table I), so far they have been mostly defined and implemented independently from each others. The gradual growth of the North Sea Offshore Grid from the interconnection of such pre-existing point-to-point HVDC links will require expansion strategies that are substantially different from those traditionally applied in AC transmission systems. The main goal of transmission expansion planning (TEP) is to determine the installation plan of new facilities (i.e. type, number, location and scheduled year) to meet the expected power demand while minimizing the cost and respecting technical, financial and reliability constraints [7]. Based on the time horizon, TEP can be classified as *static* if the solution assumes that all the additions/modifications are implemented at the same time, while it is considered *dynamic* if subsequent time steps for the recommended expansion investments are also identified. TEP approaches differ also depending on the input data uncertainty (*deterministic* vs. *non-deterministic*) and solution method. Non-deterministic TEP captures the variety of operating conditions that the system may undergo (e.g. variability of generation and consumption input data, etc.), while deterministic ones only rely on fixed scenarios. Solution methods can be based on *mathematical optimization*, where the problem is formulated in terms of an objective function subject to a set of constraints, or *heuristic* approaches relying on the step-by-step solution of the TEP according to a predefined set of rules (evaluating different alternatives with or without user interaction). *Meta-heuristic* algorithms are also commonly used to integrate the benefits of the two previous methods. Comprehensive reviews of traditional approaches to TEP in AC systems are widely available in literature [8-11].

In recent years, the deregulation of power markets determined an important change in expansion approaches. While with centralized markets, the TEP main goal is to meet the expected power demand, minimizing investment and operational costs, in the liberalized market where many players are active, different objectives and constraints are being considered [9].

III. Transmission Expansion Planning in AC/DC Systems

The increased use of HVDC technology for bulk power transmission and offshore applications produced the need for a different approach to TEP. It is recognized [12] that in order to properly quantify the benefits of HVDC interconnections and exploit their flexibility, it is crucial for expansion planning strategies to capture the HVDC operational characteristics, that are substantially different from those of traditional AC systems, as explained in Section IV.B.

Among the aspects that were most widely investigated in recent literature, there is the selection of the most convenient technological transmission alternative (HVDC vs. HVAC) for grid reinforcement, and the analyses of hybrid AC/DC grids, in particular with respect to the interactions between the newly-introduced HVDC system and pre-existing HVAC grid. Ref [13] minimizes the cost of electricity by increasing inter-zonal HVAC and HVDC links for the interconnection of asynchronous networks, by using a heuristic approach based on linear programming optimization. The analysis of [14] focuses on the inclusion of future extreme generation and different demand scenarios when determining the expansion plan ensuring minimum investment and the least-cost dispatch for the system conditions. Refs [15,16] use Mixed Integer Linear Programming to identify the convenience of including HVDC lines as new interconnection or in parallel to existing HVDC ones. The goal is to minimize both the costs of HVAC/HVDC planning and the power losses in the network. In [17] multi-terminal configurations including VSC-HVDC are considered and loss minimization is pursued, with a genetic algorithm approach, while including reliability aspects through the N-1 rule criterion. Ref [18] also minimizes the costs, considering random outages and load forecast error with a stochastic approach; it shows that, despite the higher cost, HVDC lines shorter than break-even distance may be preferred to increase the network controllability. The appropriate modeling of energy storage [19] will also have a significant impact on the development of future offshore grids, as the enabling technology for counteracting renewables' intermittency.

While the above mentioned papers deal with static expansion planning, [20] minimizes investment and operational cost, under spatial constraints, determining also the best investment time points, in addition to topology, technology and routing. Similarly, the focus of ref [21] is on cost and loss minimization with a long-term multistage expansion planning. A novel mixed-integer linear programming method is presented while considering the stochasticity of supply and demand as well as N-1 security constraints. Effect of bipolar HVDC configuration in reliability enhancement is also outlined in this paper. Refs [22, 23], present long-term dynamic fuzzy-based optimization where [22] implements a probabilistic multi-objective TEP also including generation and consumption as uncertainties. In both references it is shown how the integration of HVDC links in the power system can lead to significant reduction in cost and power losses.

IV. Transmission Expansion Planning in HVDC Offshore Grids

With the increase of the distance from shore and installed capacity of offshore wind farms, HVDC transmission through submarine cables is the only viable option. In the perspective of a future North Sea Offshore Grid, the main challenge is not the selection between HVAC and HVDC, but the proper planning of HVDC expansion in terms of topology, transmission capacity, and routing [24]. Thus, in the application of HVDC transmission for offshore applications, planning objectives and constraints can be significantly different from those of onshore applications. However, literature specifically addressing TEP in the NSOG is still limited [25]. The main objective is in most cases the maximization of social welfare while minimizing investment and operational costs. While the use of HVDC in land-based applications mostly relates to grid reinforcement, offshore HVDC is normally justified by the need of maximizing the exploitation of offshore renewables. Hence, the correct integration of information related to generation variability (due to the intermittent nature of the wind resource) becomes a mandatory requirement of TEP tools for offshore applications [26-28].

A. *Role of HVDC topology optimization*

It is worth noting that the topology optimization included in [19, 20, 24, 26-28] is mostly the result of economic considerations. However, the technical challenges associated to the practical deployment of multi-terminal and meshed HVDC networks have triggered significant research on what the best topology (e.g. radial, ring, multi-terminal, meshed) for the NSOG will be from an operational standpoint. Such studies are often based on pure dynamic simulation techniques (and not optimization) and use different performance indicators, such as evaluation of steady-state losses and fault analyses [29], grid congestions and wind utilization [30], and cost-benefit analysis of different topologies [31]. In [32], an actual optimization is carried out in order to identify the most economical topology, considering both HVAC and HVDC alternatives and optimizing the grid voltage level. Although comprehensive, the latter approach is limited to the topology optimization of a few offshore wind farms and does not target the entire NSOG.

B. Role of HVDC controllability

The possibility to control the power flow through a transmission line is the main difference when comparing HVDC to HVAC systems. This implies that the HVDC grid cannot be fully captured by an impedance representation, as in traditional HVAC planning approaches, but the controllable power flows become additional variables in the optimization. For this reason, several studies have been dedicated to optimize the operating conditions of the NSOG, with optimal power flow, under different perspectives, including steady-state optimization for the minimization of transmission losses and maximization of social welfare [33], or avoidance of critical conditions such as overcurrent and undervoltages [34]. In other cases, such analyses have focused on additional services that can be provided by HVDC links under transient and contingency scenarios, such as (primary and secondary) reserve provision [35] and increase in rotor angle stability [36]. Although such contributions do not target explicitly grid transmission expansion, the possibility of the HVDC technology to include controllers acting on different parameters and time scales, (from slow controllers for frequency regulation, to fast non-linear controllers to counteracts transient stability swings [12]) calls for a better integration of such features into expansion planning tools. A closer relation between *strategic* planning (targeting mid and long-term optimization) and *operational* planning (working on a time horizon up to 5 years) will be needed.

An overview of the main contributions on expansion planning, topology and operational optimization of HVDC systems is provided in Table II. Considered papers are classified based on time and implementation horizon, solution method, uncertainty level/type and overall analysis/ optimization objective. The specific topology (radial/ring/meshed) of the HVDC grid is considered, and, when the contribution targets the integration of the HVDC link into pre-existing HVAC networks (hybrid systems) both DC and AC grid options are ticked. Shaded rows indicate papers specifically targeting offshore HVDC systems, and meta-heuristic contributions are specified by marking both mathematic and heuristic solution methods.

V. DISCUSSION

As previously mentioned, development of the North Sea Offshore Grid based on multi-terminal/meshed HVDC technology will result from the progressive interconnection of independently designed HVDC links. In order to optimize the operation and minimize the cost of such large and complex infrastructure, a proper transmission expansion planning will be needed. Among the planning criteria that have been identified for HVDC systems there are aspects related to the reliability of the HVDC grid (including N-1 criteria, inclusion of permanent or temporary extra capacity margin and reconfiguration capability), losses minimization, and trade-off between initial investments and future benefits [37]. Proper frameworks and design approaches capable of capturing and integrating techno-economical aspects are required to address the specific challenges of offshore grids, and at present they are still underdeveloped:

- It is necessary that planning strategies and tools capture the stochasticity of natural resources, such as offshore wind, as well as the uncertainties in the consumption scenarios.
- Avoidance of renewable energy curtailment (REC) is another factor that needs to be considered in TEP. Due to the intermittency and uncertainty of renewable sources, keeping the real-time supply and demand balance in the power system has become a challenging issue. In 2013, approximately one third of the global produced wind energy has been wasted as a result of REC [38]. It is expected that the emerge of multi-terminal HVDC grids can alleviate the problem by transferring the surplus power to the neighboring load centers. However, to completely eradicate REC, comprehensive techniques to predict generation and consumption profiles, as well as integration of energy storage systems, will be key-assets to be included in TEP.
- Expansion planning should be carried out considering the integration of the HVDC offshore grid into the traditional AC power system onshore and will, hence, need to use tools suitable for the analysis of hybrid AC/DC systems.
- The high controllability of HVDC systems should be taken into account in the TEP analyses. It is important to recognize that controllability can increase the convenience of offshore HVDC deployment beyond traditional break-even point analyses. Thus, such aspect should be properly weighted at planning stage.
- It is also essential to consider and update the price of the HVDC protection system (and other emerging technology) in multi-terminal networks while minimizing cost in TEP. This equipment has relatively high price and still needs to evolve to be approved for implementation in meshed grids. DC breakers, for instance, will become a vital part of the super-grid since faults in offshore submarine cables are permanent and the system cannot restart automatically. Consequently, fast DC breakers are required to isolate the fault instead of interrupting power flow in the whole grid. In fact, DC breakers' design criteria is quite different from traditional AC ones especially because HVDC equipment is sensitive to over loads [39].
- Multi-objective optimization approaches should be applied to the expansion planning of offshore grids and a tighter integration between market-oriented/economic analyses and power system studies (including technical requirements such as static and dynamic operating constraints) should be pursued. A similar approach has been proposed for TEP in traditional AC systems [40], but very few contributions have so far considered control and stability criteria as fundamental decision variables for HVDC expansion planning [41,42].
- Hitherto, various optimization tools from programming languages (e.g C++, Python) to numerical (e.g. MATLAB, Scilab) or symbolic computation (e.g. MAPLE, Mathematica) and modeling systems (e.g. GAMS, LINGO, AMPL) have been applied based on the nature of the problem (linear, nonlinear, quadratic, mixed integer, stochastic, etc.) [11].

TABLE II: CONTRIBUTIONS ON EXPANSION PLANNING, TOPOLOGY AND OPERATIONAL OPTIMIZATION OF HVDC SYSTEMS

Paper ref.	Type of grid		Time horizon		Implementation horizon		Solution method			Uncertainty level / type				Objective	Considered topology		
											Non-deterministic						
	AC	DC	Strategic planning	Operational planning	Static	Dynamic	Mathematic	Heuristic	Simulation	Deterministic	Generation	Consumption	Outages		Radial	Ring	Meshed
[13]	X	X		X	X		X	X	X		X	X		Min. cost			X
[14]	X	X	X		X		X				X	X		Min. dispatch and investment cost	X		X
[15]	X	X	X		X		X					X		Min. planning cost and power losses	X		X
[16]	X	X	X		X		X	X					X	Min. investment and operation costs and losses			X
[17]	X	X	N.A.	N.A.	X		X	X					X	Min. losses	X		X
[18]	X	X	X			X	X	X				X	X	Min. investment, load shedding and operation cost			X
[19]		X	X		X		X				X	X		Max. social welfare and min. investment cost	X		X
[20]	X	X	X			X	X	X		X				Min. investment & operation cost	X		X
[21]	X	X	X			X	X				X	X	X	Min. cost and losses			X
[22]	X	X	X			X	X	X			X	X		Min. cost and losses			X
[23]	X	X	X			X	X	X		X				Min. cost and losses			X
[24]		X	X		X		X	X			X	X		Max. social welfare and min. investment cost			X
[26]		X	X		X		X				X	X		Max. social welfare and min. investment and operation cost	X		X
[27]	X	X		X	X		X	X			X	X		Max. social welfare and min. investment and operation cost			X
[28]	X	X	X			X	X	X			X	X		Max. social welfare and min. cost			X
[29]	X	X	N.A.	N.A.					X				X	Min. losses	X	X	X
[30]	X	X		X	X				X		X			Max. social welfare	X		X
[31]		X	X		X				X		X	X	X	Min. losses	X		X
[32]	X	X	X			X	X	X		X				Min. cost	X	X	X
[33]		X		X	X		X	X					X	Max. social welfare and min. transmission cost			X
[34]	X	X	N.A.	N.A.	N.A.	N.A.			X		X	X		Power flow study			X
[35]		X	N.A.	N.A.	N.A.	N.A.			X				X	N-1 security study			X
[36]	X	X	N.A.	N.A.	N.A.	N.A.			X				X	Transient and small-signal stability assessment	X		X
[41]	X	X		X	X		X			X				Min. installation cost and small signal stability			X

*Shaded rows indicate papers specifically targeting offshore HVDC systems. (Abbreviations: N.A.: Not Applicable)

However, the focus of the TEP problem is typically on optimization of cost and losses without taking system dynamics and stability criteria into account. Hence, new tools and approaches capable of comprehensive integration of strategic and operational planning considering technical constraints (including control aspects) need to be developed.

- The evolution of HVDC grid codes and the way they will incorporate the technical, economic, and environmental challenges while allowing market competition and maximizing supply security will have a deep impact on the feasibility of the North Sea Offshore Grid and consequently on corresponding expansion planning.

VI. CONCLUSIONS

The goal of the paper is to provide an overview of possible expansion planning strategies exportable to offshore grids based on HVDC technology and discuss their approaches and limitations. As a starting point, an updated summary of the characteristics of existing and planned HVDC links in the North Sea was given in Table I. The paper presented a comprehensive and systematic review of previous contributions on TEP for HVDC systems, which is summarized in Table II. Moreover, a critical discussion of the differences between traditional (AC) expansion planning and the corresponding counterpart for offshore HVDC grids, as well as the most challenging aspects for the development of suitable optimization frameworks for the latter has also been included.

REFERENCES

[1] Windeurope, “Wind in Power - 2016 European statistics” February 2017 https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2016.pdf (accessed 09/04/2017)

[2] F. Van Hulle, et al. "Powering Europe: wind energy and the electricity grid," A report by the European Wind Energy Association (EWEA), November 2010, p. 1–179.

[3] ENTSO-E, "10-year network development plan 2014," A report by European Network of Transmission System Operators for Electricity (ENTSO-E), 2014.

[4] Greenpeace, "PowE[R] 2030: A European grid for 3/4 renewable electricity by 2030, " A report by Greenpeace, 2014.

[5] G. Asplund, B. Jacobson, B. Berggren, K. Lindén, "Continental overlay HVDC-grid, " CIGRE B4-109, 2010, p. 1–9.

[6] A. Aguado, "Towards a European supergrid," Power Syst. Comput. Conference, 2011.

[7] J. L. Rueda, W. H. Guaman, J. C. Cepeda, I. Erlich, and A. Vargas, "Hybrid approach for power system operational planning with smart

grid and small-signal stability enhancement considerations," IEEE Transactions on Smart Grid, vol. 4, pp. 530-539, 2013.

[8] G. Latorre, R. D. Cruz, J. M. Areiza and A. Villegas, "Classification of publications and models on transmission expansion planning," in IEEE Transactions on Power Systems, vol. 18, no. 2, pp. 938-946, May 2003.

[9] C. w. Lee, S. K. k. Ng, J. Zhong and F. F. Wu, "Transmission Expansion Planning From Past to Future," 2006 IEEE PES Power Systems Conference and Exposition, Atlanta, GA, 2006, pp. 257-265.

[10] R. Hemmati, R. A. Hooshmand, A. Khodabakhshian, "State-of-the-art of transmission expansion planning: Comprehensive review, Renewable and Sustainable Energy Reviews," Volume 23, July 2013, Pages 312-319.

[11] Niharika, S. Verma and V. Mukherjee, "Transmission expansion planning: A review," 2016 International Conference on Energy Efficient Technologies for Sustainability (ICEETS), Nagercoil, 2016, pp. 350-355.

[12] M. Henderson, J. Gagnon and D. Bertagnolli, "Planning Issues for HVdc," 2006 IEEE PES Power Systems Conference and Exposition, Atlanta, GA, 2006, pp. 28-32.

[13] A. L. Abbate, F. Careri, R. Calisti, S. Rossi, and G. Fulli, "Long-term HVDC developments in the European power system: The Baltic case in GridTech analysis," in *2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG)*, 2015, pp. 283-290.

[14] V. L. M. Escobar, L. R. A. Romero, Z. A. H. Escobar and R. R. A. Gallego, "Long term transmission expansion planning considering generation-demand scenarios and HVDC lines," 2016 IEEE PES Transmission & Distribution Conference and Exposition-Latin America (PES T&D-LA), Morelia, 2016, pp. 1-6.

[15] A. H. Dominguez, A. H. E. Zuluaga, L. H. Macedo and R. Romero, "Transmission network expansion planning considering HVAC/HVDC lines and technical losses," 2016 IEEE PES Transmission & Distribution Conference and Exposition-Latin America (PES T&D-LA), Morelia, 2016, pp. 1-6.

[16] A. H. Domínguez, A. H. Escobar, and R. A. Gallego, "An MILP model for the static transmission expansion planning problem including HVAC/HVDC links, security constraints and power losses with a reduced search space," *Electric Power Systems Research,* vol. 143, pp. 611-623, 2// 2017.

[17] Z. Zhang, J. Liang, X. Wang, R. Ye and Z. Lin, "Transmission network including VSC-HVDC expansion planning based on genetic algorithm with shift operation," 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conf. (APPEEC), Xi'an, 2016, pp. 722-726..

[18] A. Lotfjou, Y. Fu and M. Shahidehpour, "Hybrid AC/DC Transmission Expansion Planning," in IEEE Transactions on Power Delivery, vol. 27, no. 3, pp. 1620-1628, July 2012.

[19] D. Azari, S. S. Torbaghan, M. Gibescu and M. A. M. M. van der Meijden, "The impact of energy storage on long term transmission planning in the North Sea region," 2014 North American Power Symposium (NAPS), Pullman, WA, 2014, pp. 1-6.

[20] H. Ergun, R. Belmans, D. Van Hertem and B. Rawn, "Long term investment optimization methodology for multi-zonal transmission expansion," 2016 IEEE International Energy Conference (ENERGYCON), Leuven, 2016, pp. 1-6.

[21] A. H. Dominguez, L. H. Macedo, A. H. Escobar, and R. Romero, "Multistage security-constrained HVAC/HVDC transmission expansion planning with a reduced search space," *IEEE Transactions on Power Systems,* vol. PP, pp. 1-1, 2017.

[22] H. Doagou-Mojarrad, H. Rastegar, and G. B. Gharehpetian, "Probabilistic multi-objective HVDC/AC transmission expansion planning considering distant wind/solar farms," *IET Science, Measurement & Technology,* vol. 10, pp. 140-149, 2016.

[23] H. Doagou-Mojarrad, H. Rastegar and G. B. Gharehpetian, "Interactive fuzzy satisfying-based HVDC/AC transmission expansion planning considering investment cost and network loss," *Initernational Transactions on Electrical Energy Systems,* Published online 18 April 2016 in Wiley Online Library, vol. 26, Issue 11, pp. 2425-2444, 2016.

[24] S. S. Torbaghan, M. Gibescu, B. Rawn and M. Van der Meijden, "A market-based transmission planning for HVDC grid—case study of the North Sea," 2015 IEEE Power & Energy Society General Meeting, Denver, CO, 2015, pp. 1-1.

[25] J. Gorenstein Dedecca, R. A. Hakvoort, "A review of the North Seas offshore grid modeling: Current and future research, " Renewable and Sustainable Energy Reviews, Volume 60, July 2016, Pages 129-143, ISSN 1364-0321.

[26] T. Trötscher, & M. Korpås, "A framework to determine optimal offshore grid structures for wind power integration and power exchange" Wind Energy, 14(8),2011, pp. 977-992 .

[27] S. Jaehnert, O. Wolfgang, H. Farahmand, S. Völler, D. Huertas-Hernando, "Transmission expansion planning in Northern Europe in 2030—Methodology and analyses," Energy Policy, Volume 61, October 2013.

[28] H. Ergun, B. Rawn, R. Belmans, and D. V. Hertem, "Stepwise investment plan optimization for large scale and multi-zonal transmission system expansion," *IEEE Transactions on Power Systems,* vol. 31, pp. 2726-2739, 2016.

[29] M. K. Bucher, R. Wiget, G. Andersson and C. M. Franck, "Multiterminal HVDC Networks—What is the Preferred Topology?," in IEEE Transactions on Power Delivery, vol. 29, no. 1, pp. 406-413, Feb. 2014.

[30] D. Huertas-Hernando, H. G. Svendsen, L. Warland, T. Trötscher and M. Korpås, "Analysis of grid alternatives for North Sea offshore wind farms using a flow-based market model," 2010 7th International Conference on the European Energy Market, Madrid, 2010, pp. 1-6.

[31] S. Cole, P. Martinot, S. Rapoport and G. Papaefthymiou, "Cost-benefit analysis of a coordinated grid development in the North Sea," 2015 IEEE Eindhoven PowerTech, Eindhoven, 2015, pp. 1-5.

[32] H. Ergun, D. Van Hertem and R. Belmans, "Transmission system topology optimization for large-scale offshore wind integration," 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC, 2013, pp. 1-1.

[33] S. Rodrigues, R. Teixeira Pinto, P. Bauer and J. Pierik, "Optimization of social welfare and transmission losses in offshore MTDC networks through multi-objective genetic algorithm," Proceedings of The 7th International Power Electronics and Motion Control Conference, Harbin, China, 2012, pp. 1287-1294.

[34] N. U. Ahmad Chowdhury and A. Yanushkevich, "Power flow analysis of meshed AC-DC super grid," 2015 IEEE Eindhoven PowerTech, Eindhoven, 2015, pp. 1-6.

[35] T. M. Haileselassie and K. Uhlen, "Power System Security in a Meshed North Sea HVDC Grid," in Proceedings of the IEEE, vol. 101, no. 4, pp. 978-990, April 2013.

[36] A. A. van der Meer, M. Ndreko, J. A. Bos, M. Gibescu, M. A. M. M. van der Meijden and W. L. Kling, "Stability assessment of VSC-HVDC connected large-scale offshore wind power: A North-Sea region case study," 2015 IEEE Eindhoven PowerTech, Eindhoven, 2015, pp. 1-6.

[37] European HVDC Grid Study Group “Technical Guidelines for First HVDC Grids” Information from the German National Committee of CENELEC, Berlin, 13 December 2012.

[38] C. Li, et al., "Comprehensive review of renewable energy curtailment and avoidance: A specific example in China," *Renewable and Sustainable Energy Reviews,* vol. 41, pp. 1067-1079, 1// 2015.

[39] R. Adapa, "High-Wire Act," IEEE Power & Energy Magazine, 2012.

[40] J. L. Rueda, W. H. Guaman, J. C. Cepeda, I. Erlich and A. Vargas, "Hybrid Approach for Power System Operational Planning With Smart Grid and Small-Signal Stability Enhancement Considerations," in IEEE Transactions on Smart Grid, vol. 4, no. 1, pp. 530-539, March 2013.

[41] A. Fuchs and M. Morari, "Placement of HVDC links for power grid stabilization during transients," 2013 IEEE Grenoble Conference, Grenoble, 2013, pp. 1-6.

[42] A. Fuchs and M. Morari, "Actuator performance evaluation using LMIs for optimal HVDC placement," 2013 European Control Conference (ECC), Zurich, 2013, pp. 1529-1534.

Atousa Elahidoost is pursuing her Ph.D. degree in model based design for the topology optimization of HVDC grids at the Norwegian University of Science and Technology (NTNU). Before, she received the M.Sc. degree in electrical engineering/electronics from the Islamic Azad University Central Tehran Branch (IAUCTB), Iran in 2011, and M.Sc. degree in electrical power engineering from NTNU in 2016. Her special fields of interest include design and optimization of HVDC grids, integration of renewable energy sources particularly solar and wind, and power system operation and stability.

Elisabetta Tedeschi received the M.S. degree (Hons.) in electrical engineering and the Ph.D. degree in industrial engineering from the University of Padova, Italy, in 2005 and 2009, respectively. From 2009 to 2011, she was a Postdoc researcher at the Norwegian University of Science and Technology (NTNU), Norway. Having received a Marie Curie Fellowship, from 2011 to 2013 she was an Experienced Researcher at Tecnalia, Spain. Between 2013 and 2014 she was a Research Scientist at Sintef Energy Research and Adjunct Associate Professor at NTNU. Since 2014, she is professor within offshore grid at the Department of Electric Power Engineering of NTNU. Her research interests include design and control of energy conversion systems, offshore transmission and distribution networks and power quality issues.