Transient Stability Analysis of an Onshore Power System With Multi-Terminal Offshore VSC-HVDC Transmission: A Case Study For The Netherlands

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***Abstract*—This paper quantifies the dynamic interaction between an onshore power system and multi-terminal voltage source converter (VSC)-based HVDC transmission systems which are used for the integration of far and large amounts of offshore wind power. Both point-to-point and multi-terminal direct current (MTDC) connection of offshore wind power plants have been investigated. A 2025-2030 scenario for the power system of the Netherlands and its neighbors has been created as a case study. Special attention is given to the transient stability of critical generators in the Dutch power system for situations with large amounts of onshore and offshore wind power production. Time-domain simulations are performed using the commercial software PSS®E, augmented with user-defined models, for a fourteen-terminal MTDC network which extends from Germany via Netherlands to Belgium. The studies highlight fault propagation in a wider neighborhood when MTDC technology is used for the connection of wind power in the North Sea.**

***Index Terms*—HVDC transmission, multi-terminal, power system stability, offshore wind integration, PSS®E**

I. INTRODUCTION

The European Union boasts ambitious targets for its renewable energy development plan. By 2020, 20% of the gross final energy consumption should be met by the exploitation of renewable energy sources. Being a strategic and largely untapped energy resource, offshore wind power is anticipated to play an important role in achieving this goal, especially for the North-Sea countries.

High voltage direct current transmission based on voltage sourced converter technology (VSC-HVDC) is the best solution for the connection of large offshore wind power plants that are located far from shore. The construction of multi-terminal VSC-HVDC connections (VSC-MTDC) in the North Sea region would advance the integration of offshore wind power and further foster the internal European electricity market operation. Notwithstanding these foreseen benefits, it is key to investigate the consequences of interconnecting this new type of infrastructure to the existing power systems in terms of dynamic behavior.

This paper specifically focuses on transient stability effects of MTDC transmission, using a dynamic model of the power system of Netherlands and its neighbors as a case study. Seven different VSC connection points for offshore wind power (three in the Netherlands, three in Germany, and one in Belgium) have been considered for a 2025-2030 future scenario. Two types of VSC-HVDC network configurations are modeled and compared: point-to-point links and a MTDC interconnection that extends from Germany via the Netherlands to Belgium. Three snapshots of the Dutch power system are evaluated, each reflecting situations of different conventional and renewable generation, load and international power exchange.

The paper is organized as follows. First, the applied user-defined VSC-MTDC modeling as well as control strategies for both normal and emergency operation will be described. Next, the specifications for the onshore and offshore network models and corresponding snapshots are given. The dynamic behavior of the integrated system is assessed. The paper ends with conclusions and directions for future research.

II. MODELING FRAMEWORK

The commonly-used approach to represent the AC network and converters in transient stability studies is by quasi-stationary averaged models. At present, standard dynamic models exist for point-to-point VSC-HVDC connections, however these cannot be easily extended to every conceivable DC network topology [1]. Therefore, a user-defined generic model for a VSC-MTDC transmission system, which is compatible with the dynamic power system model for the Netherlands in PSS®E, was developed in this work.

A. VSC Dynamic Model for Power System Stability Studies

The VSC AC terminal is connected to the AC power system via a phase reactor and a transformer. The converter itself is a controlled voltage source from the AC side while on

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the DC side it is modeled by a current injection [2]. The AC and DC sides are coupled by the active power balance and, for the sake of simplicity, converter losses are not considered. Figure 1 presents the equivalent circuit which demonstrates the coupling of the AC and DC sides of the VSC.

In PSS®E the dynamic models of all generation units are represented by controlled Norton-equivalent current sources [1]. For that reason the equivalent model of the VSC on the AC side has been transformed to a controlled current source equivalent. Figure 2 illustrates the dynamic model of the VSC terminal. On the DC side, the HVDC cables are represented by a π-equivalent model implemented by a state space representation which can be extended to any conceivable DC network configuration [2].

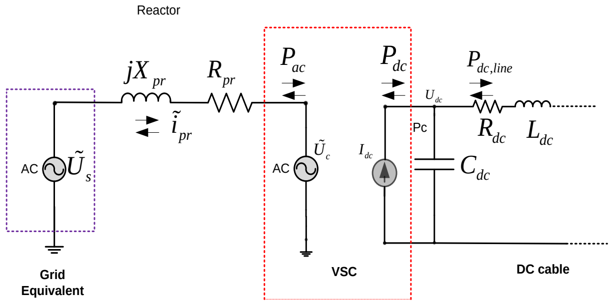

Figure 1. Equivalent circuit of the AC and DC side of the VSC.

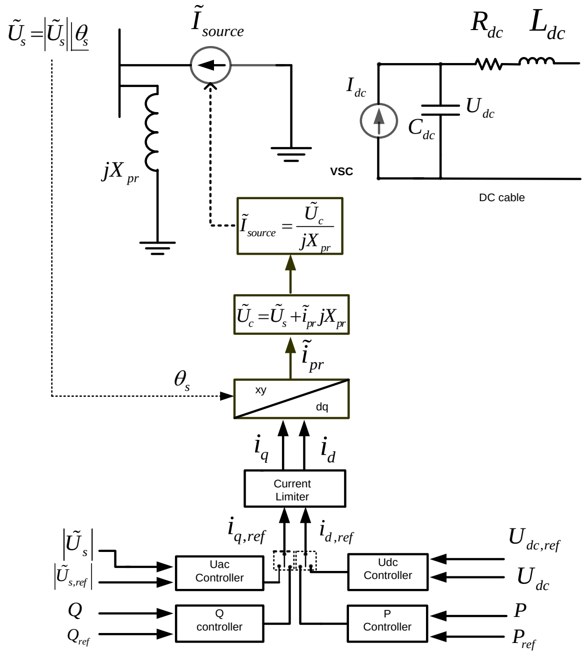

Figure 2. Model of the VSC in PSS®E (phase reactor resistance R_{pr} neglected).

For the network dynamics, only the fundamental frequency has been taken into account. AC system variables (e.g. voltages and currents) are represented by time-varying phasors in per unit notation. Furthermore, time constants which are small in comparison with the AC-side time constants, such as those associated with the power electronic modulator (20 ms), are neglected.

B. *Controls Implemented for the MTDC Network*

Most VSCs have a cascaded control structure that comprises an inner current control loop and outer controllers which implement vector control [3]. The most important benefit of vector control is the decoupled control of active and reactive power. All the controls are implemented with proportional-integral (PI) controllers. The inner controller describes the closed-loop dynamic behavior of the current flowing through the phase reactor. The outer controllers control active and reactive power flows as well as the AC and DC voltage at the VSC terminal (a subset consisting of one variable for each of the d and q axes, depending on strategy).

The control of the direct voltage is important for the operation of a future VSC-MTDC network. It is related to the power balance at the DC side of the converter station. A high overvoltage may activate protection mechanisms while significant direct voltage drops may trigger non-linear PWM modulation of the VSC [4]. For the above reasons the direct voltage should be maintained within stiff operating limits ensuring the smooth operation of the MTDC network.

The control of the direct voltage can be assigned either to one converter station or to a group of converters. In vast VSC-MTDC networks it is preferable that more than one converter station is in direct voltage control mode. The main reason for this redundancy is the limited current-carrying capacity of a single VSC and the possibility of converter outage as a result of disturbance.

In this paper the direct voltage droop control method is utilized [5]. The droop control method is capable of performing proportional power sharing (i.e. sharing fluctuations in wind power in-feed proportional to the controller's voltage droop). It consists mainly of a proportional controller which represents a droop line characteristic. This droop line introduces a unique linear relation between the direct voltage and the d-axis component of the converter AC current, and hence active power. In this way the variations of the DC voltage are related to variations of active power at the converter station.

C. *Model of the Current Limiter*

The AC current of the VSC should be limited at its maximum acceptable value. More specifically the onshore VSCs are capable to provide fault current as long as it does not damage the sensitive power electronic switching devices. This protection scheme has to do with thermal limits of the semiconductors. Several strategies can be followed for the limitation of the VSC current, such as prioritizing either the d-axis component, the q-axis component, or proportional limiting [4]. In this paper proportional limiting is used.

D. *Fault Ride-Through Method*

When a fault occurs at the AC side, the active power that cannot flow into the AC onshore network due to the voltage dip will create a direct voltage increase on the DC side. This happens as a result of power surplus which is instantly stored in the capacitors of the DC grid. To prevent disconnecting the VSC-MTDC grid entirely, the fault ride through (FRT) method applied in this work employs DC choppers connected at the DC side of the onshore VSCs [6]. These are activated under emergency conditions, i.e. when direct voltage rises above 1.1 p.u. In this way the triggered DC chopper will dissipate the power that cannot flow to the AC network keeping the direct voltage at acceptable operating levels.

E. Dynamic Model of the Onshore Power System

The Dutch high-voltage transmission system consists of four voltage levels: 380kV, 220kV, 150kV, and 110kV. The 380kV and 220kV transmission system is mainly responsible for bulk power transfers while the 150kV and the 110kV are functioning as sub-transmission systems. The main ring is at 380kV level with several radial branches. In the Northern part of the country there is a second ring at 220kV level. Figure 3 introduces the present situation of the Dutch power system, including foreseen reinforcements for the 2025-2030 scenario. Additionally, two asynchronous interconnectors using classical HVDC, namely the NorNed link (700MW) and the BritNed link (1000 MW) are currently in operation.

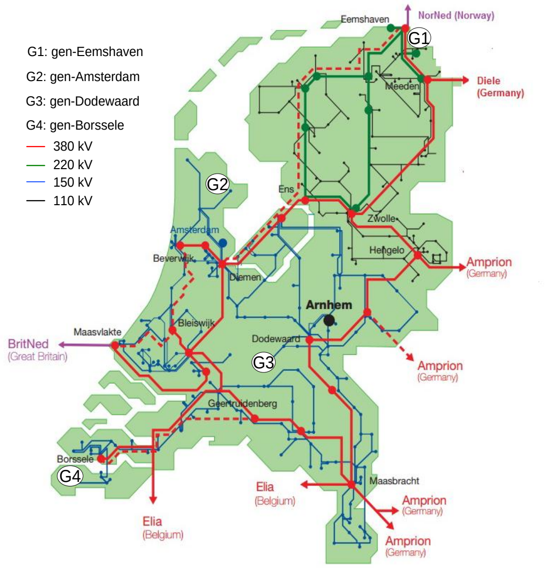

Figure 3. Present situation of the Dutch high voltage transmission system.

A detailed dynamic model of the Dutch network, including a reduced model of the surrounding countries, has been used in this work. All synchronous generators are modeled by 6th order IEEE standard models with dedicated parameters. Generators larger than 100 MW are modeled with excitation systems and governors. The German and Belgian parts of the model consist only of the bulk transmission system with directly connected generators. The largest generators are modeled by standard dynamic models with excitation systems. The rest of the ENTSO-E network is represented by aggregated models.

F. Dutch Power System Commitment Schemes

Several plausible commitment and dispatch schemes of the Dutch generators (snapshots) are selected as operating points that reflect a particular 2025-2030 network situation. All the planned network reinforcements at the 380kV level of the Dutch transmission system until the year 2030 as given by transmission system operator TenneT have been included in the existing dynamic model. Three snapshots have been selected for the time domain simulations. Figure 4 provides a graphical representation of the three selected snapshots.

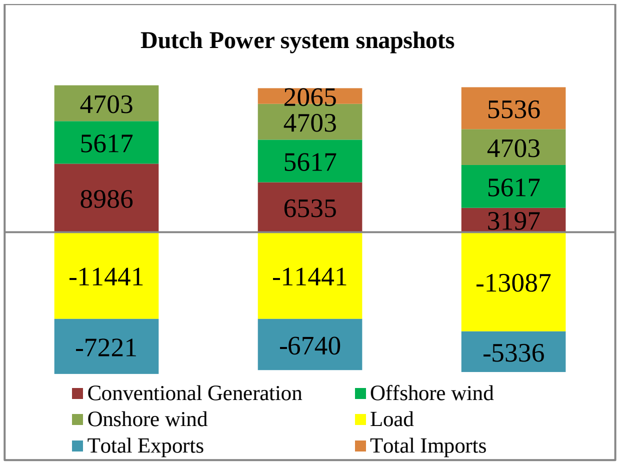

Figure 4. Selected snapshots of the Dutch Power system (quantities in MW).

G. Offshore VSC-HVDC Transmission System

Two types of VSC-HVDC system configuration have been considered. Aggregated dynamic models have been used to represent a number of offshore wind zones per country. The reason for this aggregation is that the main focus will be on the interaction between the large onshore AC network and the VSC-HVDC connection schemes. Furthermore no detailed information about the type of wind turbines employed in this future scenario was available. Hence, the full-converter direct drive wind turbine dynamic model available in PSS®E has been used [1].

1) Type 1: 2025-2030 network model with point-to-point connection of offshore Wind Power Plants

In this configuration, every offshore wind zone (3 in Netherlands, 3 in Germany and 1 in Belgium) is connected per country via a point-to-point VSC-HVDC link to the relevant feed-in onshore AC substation as given in table 1.

TABLE I. OFFSHORE WIND POWER PLANTS CONNECTION POINTS

Zones of offshore wind power plants per country	Grid feed-in point 380kV network	VSC-HVDC link capacity (MW)	Distance to shore (km)
Sudlich Amrumbank (DE)	Unterweser	1000	130
Hochsee Sud (DE)	Conneforde	5000	150
Nordlich Borkum (DE)	Diele	1500	90
Eemashaven I&II (NL)	Eemshaven	1200	90
IJmuiden (NL)	Beverwijk	3000	120
Borssele I&II (NL)	Borssele	1200	50
Thorntonbank (BE)	Eeklo-Noord	570	40

The rated direct voltage of all VSC-HVDC links is assumed ±450 kV. Currently the largest commercial offshore application (ABB HVDC Light) uses ±320 kV direct voltage level at 1200MW. However, ENTSO-E does not foresee any technical obstacles to achieving higher voltage levels by 2025-2030 for offshore transmission systems.

2) *Type 2: 2025-2030 network model with VSC-MTDC interconnection of offshore Wind Power Plants*

In the second offshore transmission system configuration to be evaluated, the seven areas assigned for development of offshore wind in the Netherlands, Germany and Belgium will be connected to the VSC-MTDC network as illustrated in Figure 5. The same onshore power system connection points have been considered as for the point-to-point configuration. A sequential AC/DC power flow algorithm is used to initialize the states of the DC network model [2].

All onshore converters are in direct voltage control mode applying the droop control method. The market power dispatch scheme implemented is the proportional power sharing which means that the generated offshore wind power is shared among the onshore VSCs according to the predefined ratio of the onshore VSCs droop line characteristics [5].

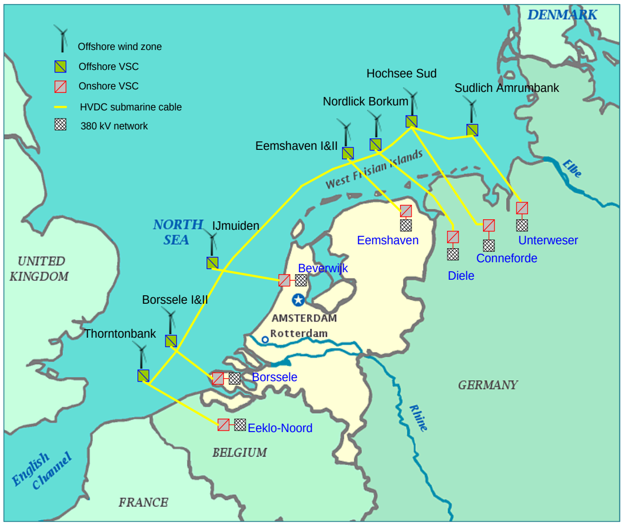

Figure 5. Transnational MTDC network.

III. SIMULATION RESULTS

The two types of VSC-HVDC configurations will be analysed for a 150ms (typical protection clearing time) three-phase bolted short circuit at the AC side of the Eemshaven 380 kV converter station. Comparing the point-to-point and MTDC connection, as illustrated in figure 6, it can be observed that the main difference is the additional injection of active power or else "overshoot" of active power during the fault in the case of the VSC- MTDC network.

Following the fault at the Eemshaven onshore VSC, the active power injection at the fault location will drop to zero. At the same time the offshore converters would continue to inject the power generated by the wind power plants and the balance between the generated power and the injected power into the AC network will be lost. This power surplus will instantly create an overvoltage at the DC side. As soon as the direct voltage reaches a threshold value the DC choppers will be activated. The active power that cannot flow to the AC network will be dissipated by the DC choppers installed at the onshore VSCs. In this way the direct voltage is successfully restricted at predefined levels during the fault, as shown in figure 7, where the time domain variation of the direct voltage profiles for the point-to-point and MTDC connections are given. The droop controllers will respond to this DC overvoltage by increasing the active power injection at the relevant converter stations. This is the main reason for the active power overshoot in figure 6. Additionally, it appears that there is significant sensitivity of the size of the active power overshoot to location of the fault, as illustrated in figure 8.

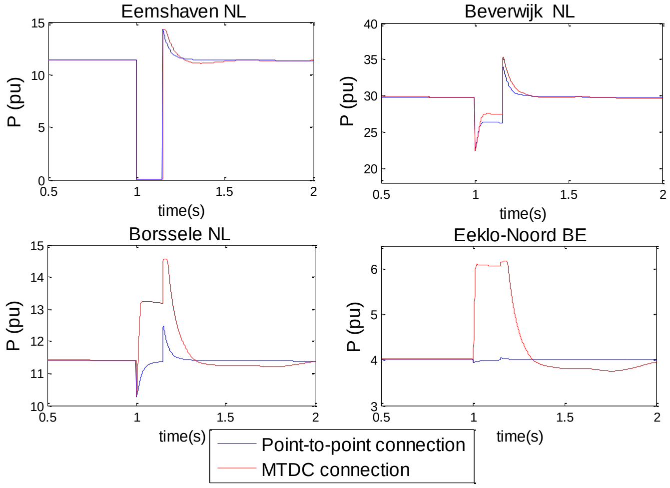

Figure 6. Power injection of the onshore VSCs (point-to-point and MTDC connection, S_b=100 MVA).

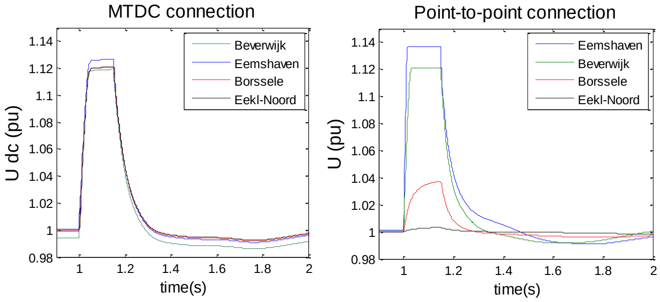

Figure 7. Direct voltage variation at the onshore converter stations (point-to-point and VSC-MTDC connection) for a 150 ms fault in Eemshaven VSC.

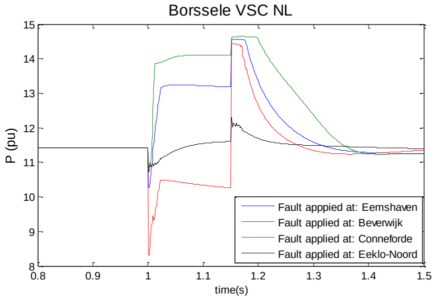

Figure 8. Sensitivity of the active power dynamic response of the Borssele onshore VSC to the fault location (S_b=100 MVA).

One major conclusion that can be drawn is that in the MTDC configuration the DC side voltages of the converters are coupled more strongly together and vary in the same direction, even for remotely located converter stations. A converter located relatively far from the fault location (such as the Borssele VSC) experiences a small AC voltage drop but high DC overvoltage which results in a high active power “overshoot”. This is also the case for the Eeklo-Noord VSC in Belgium.

With regard to the sensitivity of the dynamic response of synchronous generators to the VSC-HVDC offshore grid configuration, the time domain simulations reveal little sensitivity. Particularly, as it can be seen in figure 9, the dynamic response of selected generators in the Dutch system is nearly similar for point-to-point and VSC-MTDC configurations. The only exception is the case of the generator Borssele (located at the Borssele substation) where there is a slightly different response during the first few seconds as a result of the overshoot that appears in the grid-side converter station of the Borssele VSC.

Finally, the performance of the grid-side VSCs operating in the transnational MTDC network will be evaluated against the commitment and dispatch scheme of the Dutch generation system. For the three selected snapshots it can be seen in the top half of figure 10 that there is a growing trend in the amplitude of oscillations as a result of less Dutch conventional generation being committed. However, this trend does not illustrate itself in the post-disturbance dynamic response of the onshore VSCs. Figure 10 also shows the active power profiles of the onshore VSCs operating in the transnational MTDC network for the three selected onshore power system snapshots of figure 4.

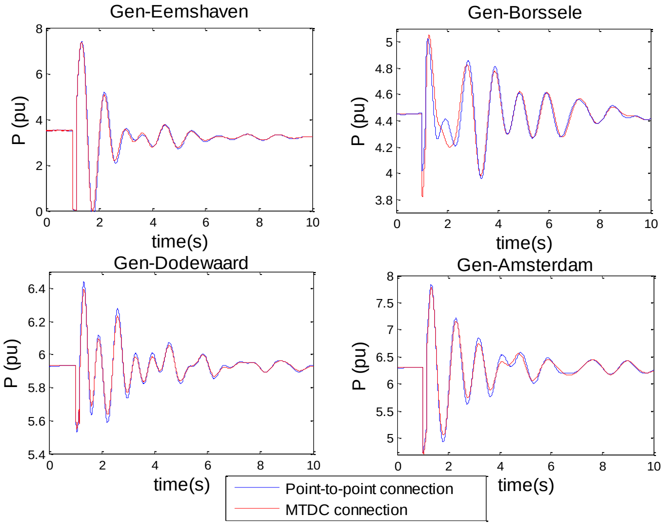

Figure 9. Sensitivity of the dynamic response of selected generators in the Dutch power system to the VSC-HVDC configuration.

IV. CONCLUSION

This paper assessed the consequences of VSC-HVDC offshore wind connections in the North Sea on transient stability of the onshore power system. Several topologies and commitment/dispatch schemes were investigated. Based on the snapshots analyzed through time-domain simulations, the main difference between point-to-point and VSC-MTDC grid configurations is the propagation of AC faults over larger distances via the VSC-MTDC network. The latter manifests itself as an active power “overshoot” visible at the AC side of remote onshore converters.

Additionally, the simulations results reveal that there is little difference between point-to-point and MTDC network connection in terms of transient stability of conventional generators in the Dutch power system.

Finally, based on the introduced case studies and disturbances simulated, it seems that the post-disturbance dynamic response of the onshore VSC stations does not vary significantly between the three selected power system commitment and dispatch schemes.

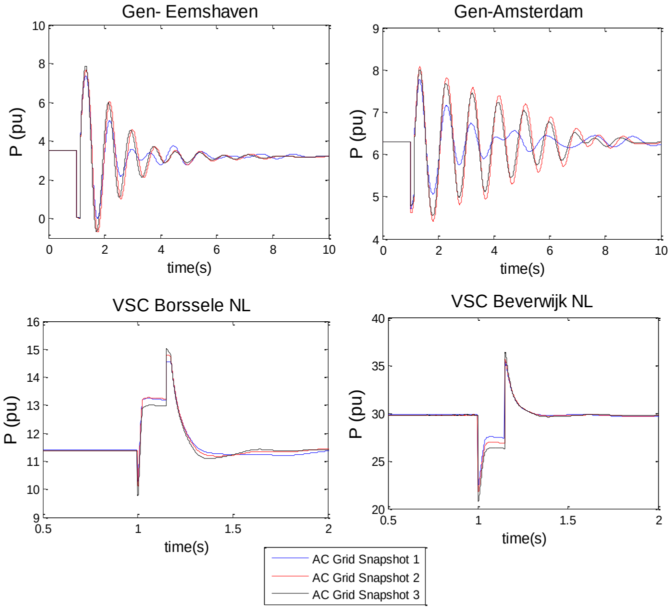

Figure 10. Sensitivity of the commitment and dispatch scheme on selected synchronous generators and selected onshore VSCs in the MTDC network.

V. REFERENCES

[1] Siemens PTI, PSS®E 32.0.5, “Program Operational Manual”, Oct.2010.

[2] P. J. D. Chainho, A. A. van der Meer, R. L. Hendriks, M. Gibescu and M.A.M.M. van der Meijden, "General Modeling of Multi-Terminal VSC-HVDC Systems for Transient Stability Studies" *6th IEEE Young Researchers Symposium, Delft, Netherlands, 16-17 April 2012.*

[3] S. Cole, J. Beerten, R. Belmans, "Generalized Dynamic VSC MTDC Model for Power System Stability Studies," *Power Systems, IEEE Transactions on , vol.25, no.3, pp.1655-1662, Aug. 2010.*

[4] C. Ismunandur, A. A. van der Meer, R. L. Hendriks, M. Gibescu and W. L. Kling, "Control of Multi-terminal VSC-HVDC for Wind Power Intergration using the Voltage-margin Method," *in in Proc. 9th International workshop on Large Scale Integration of Wind Power into Power systems as well as on Transmission Networks for Offshore Wind Power Plants, Quebec City, Canada, Oct. 18-19, 2010,* pp. 427-434.

[5] X. Lie, Y. Liangzhong, M. Bazargan, "DC Grid Management of a Multi-terminal HVDC Transmission System for Large Offshore Wind Farms," *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference on* , vol., no., pp.1-7, 6-7 April 2009.

[6] C. Feltes, H. Wrede, F. Koch and I. Erlich, "Fault Ride-Through of DFIG-Based Wind Farms Connected to the Grid through VSC-Based HVDC link," *Power Systems, IEEE Transactions on vol.24, Issue3, p.p 1537-1546* , 2009.