Project title	Electromagnetic Transient study of wind farms connected by HVDC
Project number	TG1-21
Organisation	Chalmers University of Technology, Electric Power Engineering
Project leader	Massimo Bongiorno
Other participants	Mebtu Beza (Postdoc)
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Participating companies	ABB, Vattenfall, Svenska Kraftnät, Mitsubishi Vestas Offshore Wind

Project description

An increasing amount of remote large-scale offshore wind farms are being connected to the main onshore grid by means of high-voltage direct current (HVDC) systems [1]. The remote sites enable good wind conditions, generation out-of-sight and fair construction conditions for wind turbines. However, the complex interaction between the interfaces of the wind turbine generators (WTG) and in particular their converter controls, the cable systems, the offshore substation components and offshore HVDC converter can give rise to harmonic and resonance phenomena as well as in-proper control or protection actions [2–4]. Both HVDC manufacturers and WTG manufacturers have a principal interest in assuring that their respective equipment and designs are compatible with the electrical infrastructure of wind power plants, both on- and off-shore. Hence, the operation of the wind turbines, the wind power plant controllers and the HVDC Voltage Source Converter (VSC) station control require investigation in order to ensure a good power quality and at the same time to avoid over-engineering costs.

The overall objective with this study is therefore to safeguard the robustness and reliability of future investments in large-scale integration of wind power generation connected to the main grid by HVDC through analytical investigation and the development of relevant simulation models. Furthermore, the project aims to increase and broaden the knowledge base and competence in the field of electromagnetic transient behavior, voltage stability and harmonics/resonances of HVDC connected wind farms. More specifically, the study shall have the objective to:

- Obtain insight into harmonic susceptibility and emission characteristics of relevant equipments in WTG, HVDC system and the ac collection network.
- Obtain representative simulation models of relevant equipment, adequate for case studies and phenomena of interest.
- Perform in-depth analysis of interaction between the HVDC converter control and the wind turbine converter control in order to identify root causes of potential oscillations.
- Investigate possible impacts on the onshore ac grid when oscillatory interactions arise between the offshore HVDC station and the wind turbine converter controls.
- Define key parameters and make sensitivity analysis with respect to stability and robustness of the system.
- Develop mitigation methods such as design guidelines and control strategies to avoid potential resonant phenomena in future.
- Perform a list of case studies, including variations in operating points, number of turbines, feeder cables and control parameters.

The investigated system is similar to the one depicted in Fig. 1, where the wind turbines are equipped with Full Power Converters (FPC) and the HVDC converters are based on a modular multilevel converter (MMC). An offshore wind farm with a 66 kV collection cable system with a base power of 400 MW has been considered for the investigation. The dc-link voltage of the HVDC system is 300 kV and 8 MW wind turbines equipped with 0.69/66 kV step-up transformers have been selected for the study.

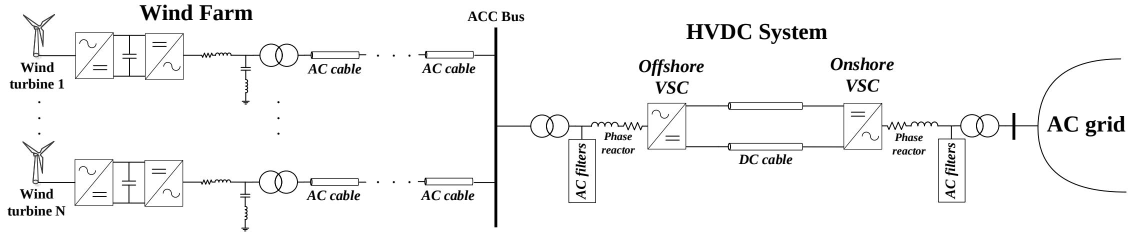

Fig. 1. Schematic of the offshore wind farm connected to the onshore grid through HVDC system.

To do the investigation, frequency-dependent impedance models are derived on the ac side based on the various control structures for the wind turbine and HVDC converters. Using the impedance models of the converters together with the impedance of the offshore ac grid, stability of the system can be investigated. The frequency-based stability tool is useful as it does not require full knowledge of the control system for each converter but instead its frequency characteristics. Moreover, frequency-dependent parameters as well as time delays can be accurately represented in the models. The method also provides a useful tool to identify contribution of different system components in the stability of the interconnected system [5].

[1] P. Bresesti,W. L. Kling, R. L. Hendriks, and R. Vailati. Hvdc connection of offshore wind farms to the transmission system. *IEEE Trans. Energy Convers.,* 22(1):37–43, March 2007.

[2] S. P. Teeuwsen, R. Zurowski, L. J. Cai, S. Jensen, A. Osmanbasic, and F. Gafaro. Transient interaction study for VSC-HVDC connected offshore wind park considering original controls. In *2014 IEEE PES General Meeting — Conference Exposition*, pages 1–5, July 2014.

[3] C. Buchhagen, C. Rauscher, A. Menze, and J. Jung. Borwin1 - first experiences with harmonic interactions in converter dominated grids. In *International ETG Congress 2015; Die Energiewende - Blueprints for the new energy age; Proceedings of*, pages 1–7, Nov 2015.

[4] H. Liu and J. Sun. Voltage stability and control of offshore wind farms with ac collection and HVDC transmission. *IEEE J. Emerg. Sel. Topics Power Electron.,* 2(4):1181–1189, Dec 2014.

[5] M. Beza, M. Bongiorno, and G. Stamatiou, "*Analytical Derivation of the AC-Side Input Admittance of a Modular Multilevel Converter With Open- and Closed-Loop Control Strategies", IEEE trans. Power Del.*, May 2017.

Results

In order to achieve the project goals, the study on the stability of offshore wind farm connected by MMC-based HVDC system has produced the following results.

- A frequency-dependent impedance model of A FPC-based wind turbine with an inner current controller and various outer loop controllers has been derived. The derived impedance models are verified against a time domain switching PSCAD model.
- The input impedance of an MMC both with ac-side open-loop and closed-loop operation has been derived. The derived impedance models are verified against a time domain switching PSCAD model.
- The stability of an aggregate model of a 400 MW wind farm connected by an HVDC system with a total dc-link voltage of 300 kV has been investigated. In the aggregate model, the wind farm is represented with the grid-side converter with a variable input power on the dc side, whereas the HVDC system is represented by the offshore converter with a constant dc-link voltage. The offshore ac network is represented by transformers, filters and a single 66 kV ac cable model. Using a frequency domain approach, it has been shown that the stability of the aggregate system can be predicted. It is demonstrated that the nature of resonances observed are dependent on the operating points, the selection of the controller parameters and the available passive components.
- In the studied wind farm - HVDC system, the wind farm is represented with the grid-side converter with a variable input power on the dc side, whereas the HVDC system is represented by the offshore converter with a constant dc-link voltage. The impacts of the simplification in the system

representation (such as aggregation, the onshore VSC station, the wind turbine system) are investigated.

- The impact on stability of both open- and closed-loop control approaches for the offshore MMC has been investigated.
- Method of aggregating multiple turbines in a wind farm system has been developed. The impact of the aggregation in the system stability study has been investigated.
- Possible sources of unstable resonances in a wind-farm HVDC system such as converter control parameters and nature of passive components has been identified and possible solutions has been suggested.
- The impact of offshore oscillatory oscillations on the onshore ac grid has been investigated.
- The impact of alternative control strategies for the FPC-based wind turbine (control structures without PLL such as alpha-beta control, virtual-machine control, and power-synchronization control) on stability of the wind-farm HVDC system has been investigated.

Fulfilment of SWPTC's goals

The aim of this project is to ensure the robustness and stability of offshore wind farms connected to the onshore grid though HVDC. In addition to increasing the knowledge base and the competence in the field of electromagnetic transient behaviors in Chalmers, the project results help the relevant industries to avoid unnecessary investments related to the investigated phenomena. In addition, one of the SWPTC's goals focuses on wind farm collection grid and possible issues that might arise in case of the use of DC technology and thereby high penetration of power electronic controllers. This has be fulfilled with in this project, by investigating causes of system failures and suggesting possible solutions in a wind farm – HVDC system.

Deviations from project plan

No major deviations from the project plan.

Publications

From the activities of the project, the following publications are produced.

- M. Beza, M. Bongiorno, and G. Stamatiou, "Analytical Derivation of the AC-Side Input Admittance of a Modular Multilevel Converter With Open- and Closed-Loop Control Strategies", IEEE trans. Power Del., May 2017.
- M. Beza, and M. Bongiorno, "Stability of grid-connected modular multilevel converter with open- and closed-loop ac-side control", European Conference on Power Electronics and Applications, Sept. 2017.
- M. Beza and M. Bongiorno, Identification and mitigation of unstable resonances in a wind-farm connected by an HVDC system, IEEE trans. Power Syst. (under submission process)

External activities

There has been a close cooperation with the participating companies (ABB, Vattern fall, Svenska Kraftnät and Mitsubishi Vestas Offshore Wind) during this period. Parameters for the various models have been suggested and comments on the project progress have been provided through three reference group meetings at Chalmers. A one week research visit to Vestas also took place for model verification.