

Power Delivery in Multiterminal VSC-HVDC Transmission System for Offshore Wind Power Applications

R. da Silva, R. Teodorescu, *Senior Member, IEEE* and P. Rodriguez, *Member, IEEE*

Abstract—This paper deals with one of the challenges in the field of offshore wind power systems: power transmission among the wind farms and the land when there is more than one AC grid to be considered. This case is known in the literature as multiterminal connection. The proposed studies are going to present three strategies in order to connect one offshore wind farm and two AC grids with different power ratings. The first strategy shows the easier case when one onshore station defines the power transmission and it is followed by the situation when droop control is applied. The final scheme is focused on the technique which a central power control is able to manage the onshore stations. The results are compared using EMTDC-PSCAD platform.

Index Terms—Multiterminal VSC-HVDC, voltage source converters, wind energy.

I. INTRODUCTION

From the beginning of the history, wind energy was used in windmills in order to pump water or grind grains. Nowadays, mainly after the 70s, after the first oil crisis, this source of power have been considered as a alternative energy resource. Data from The U. S. Department of Energy Report [1], published in 2009, shows that nearly 11% of the total installed capacity come from renewable energy sources and over half of this plot comes from wind energy.

Compared with the other source of renewable energies, excluding hydropower, wind turbines have the biggest participation in the market of energy, which represents that this kind of source is the fastest growing renewable electricity technology. The main reason to that is related to the cost of the whole wind power system. Currently, wind power is a fully established branch on the electricity market [2]. Energy production in not the only criterion to be considered when installing new wind turbines; cost, efficiency, the impact on the environment and the impact on the electric grid are some of important issues of significant interest when making decisions about new wind turbines installations.

With the growth in the demand, the power ratings and size of the wind turbines have been increasing during the years. Adding the fact that the onshore sites available to the use wind farms are decreasing and the offshore wind to have an annual wind speed bigger than on shore, the current trend in

R. da Silva and R. Teodorescu are with the Department of Energy Technology, Aalborg University, Aalborg, 9220-Denmark. (e-mails: rds@iet.aau.dk and ret@iet.aau.dk)

P. Rodriguez is with University of Catalonia, Barcelona, Spain. He is a visiting professor at the Department of Energy Technology, Aalborg University, Aalborg, 9220-Denmark. (e-mail: prodriguez@ee.upc.edu)

the wind power industry is to move from the land to places far away to the coast.

As consequence, the drawbacks related to the long distances transmission must be considered. One of the possible candidates to overcome this problem is the use of High Voltage Direct Current (HVDC) transmission system using Voltage Source Converters (VSCs). One of the most important advantages of this technique compared with the traditional HVAC case is the losses minimization for long distances. Lower cost, Right-of-Way, controllability, black-start capability and AC network stabilization can also to be listed as benefits of VSC-HVDC [3], [4].

With VSC-HVDC, the idea of supergrids, which aims to connect a wide area using long distance transmission lines in order to take advantage of renewable sources distantly located, became possible through Multiterminal VSC-HVDC in this case. A multi-terminal HVDC system consists of more than two converters connected through DC line cables and sharing the same DC bus [5], [6], [7]. Multi-terminal HVDC system has advantages over two-terminal HVDC one in many aspects such as control flexibility, reliability and economy.

In the multi-terminal HVDC case, there are some benefits that can be listed: bulk power transmission, AC network interconnection over a long or medium distance, economical advantages such as total installed converter rating in an MTDC system is usually less than that of several equivalent two HVDC systems, MTDC systems offer low cost transmission lines and/or cables, the inherent overload capability of MTDC transmission lines can increase the capacity of transmission corridors. Some technical advances can also be found in this kind of configuration.

Examples for them are MTDC systems provide greater flexibility in dispatching transmitted power, in a larger interconnected power system, MTDC systems can provide a powerful control action to damp out troublesome electromechanical oscillations, in conjunction with phase shifting transformers and generation shifting, MTDC systems may be used to enforce desired power flow patterns in a large interconnected power system, the fundamental control principle for MTDC systems is a natural generalization of that for existing two HVDC systems.

When more than one receiving-end station is considered, the power flow needs to be controlled in order to achieve a determined power exchange among interested partners who divide the same DC link. Due to the random behaviour of the wind, the power, which one is delivered to each station, changes.

Also, different AC grid requirements can be permitted where the onshore stations are connected. Due to that, the share of power can change and must be controlled. This paper deals with this control topic.

The following section presents the overall description of the system which is going to be analyzed. After that, it is described the modelling issues and control strategies presented in each converter of the system. Power sharing techniques are given in the Section IV followed by simulation results. Discussions finish the paper summarizing the main results.

II. SYSTEM DESCRIPTION

The system layout which is going to be used consists of a wind farm, an offshore HVDC station, two onshore HVDC stations and two AC grids.

The wind farm is modelled as a current source, in order to emulate the wind and a turbine side converter, and a two-level converter connected to the AC offshore grid. A transformer makes this connection. A HVDC station is formed by a insulation transformer and the power converter. Two different paths make the link between two on shore stations and, in land, the onshore stations are connected to AC grids. The single line block diagram is showed in the Figure 1.

The wind farm aggregated model and the offshore HVDC station are sized in 1pu of power. The onshore station connected to the AC system 1 is also sized in 1pu. The second receiving end converter has 0.5pu of power. The distances between the two land stations are also distinct. The second link is 1.5 times the first one. The cables are modelled as pi-sections of 50km each.

III. SYSTEM MODELLING AND CONTROL

Each converter presented in the Figure 1 has its own control scheme and they are applied according to the function presented by each of the converters.

All of control schemes are based on inner and outer control strategies. The modelling procedure follows the theory firstly presented in [8] and extended by [9], [10], [11]. The $p-q$ theory is the base of the control strategy by the most number of VSC-HVDC control strategies [12], [13], [14], [15], [16], [17], [18], [19], [20].

A. Wind Farm Converter Control

The wind farm converter takes the energy from the wind (modeled as a simple current source) and pushes it into the offshore grid. The DC voltage control senses the variation of power due to the charging and discharging of the DC capacitor.

This outer control imposes in the AC grid a certain amount of current proportional to the wind power. Reactive currents can also be injected in the system due to the decouple control in the synchronous reference frame. A Phase Locked Loop (PLL) synchronizes the wind farm currents according to the offshore AC voltages.

B. Offshore HVDC Station Control

The offshore HVDC station has the rectifier task, it means that all the AC energy delivered by the wind farm is transformed in DC and sent to the land through the DC cables.

However, this converter must create an AC grid since that the wind farm VSCs need a AC voltage to operate properly.

In order to satisfy those requirements, this station is equipped with a outer control loop which is able to control the AC voltages on the point of common coupling between the wind farm converter and the offshore HVDC station. Also, the energy from the wind farm is sense by the capacitor, but in this case the one which is connected in the AC filter [21].

C. Onshore HVDC Station Control

For this case, some changes appear according to the power sharing control strategy. The common block is the inner control loop which is also presented by the previously converters. However, the outer controllers are different. For the first strategy (which is going to be presented in the following) the outer loop of the onshore station has the same structure which is implemented in the wind farm converter: DC voltage control. To the second onshore converter, the current on the direct axis is set according to a rated power previously defined. For the other cases, the DC voltage control is controlled using droop technique or central station controllers.

IV. POWER SHARING CONTROL

The most existing connection using high voltage direct current in the world are point to point. It means that only one sending-end and one receiving-end stations are available. This kind of connection does not allow the expansion of physical interconnection capacity and improvements of the possibility of power exchange.

Nowadays, multiterminal connection is the solution for this lack and it is suitable solution that can provide the offshore wind farm connection and also that can facilitate the transnational exchange with a high cost efficiency [22].

Though, increasing the number of connections means that more complex the system becomes. The control of DC voltages and the power sharing which guarantees the power exchange between the inverter stations can bring some complications. Including the random behaviour of the wind energy, at any moment is not possible to precisely determine the power which can be delivered.

In order to explore these problems, three control strategies, in order to guarantee the DC voltage balance and power sharing, are going to be compared. The strategies are going to be label as following:

A. Scheduled power control;

B. DC voltage droop control;

C. Central DC voltage control.

These sentences are used with the only objective of keeping text clear and objective.

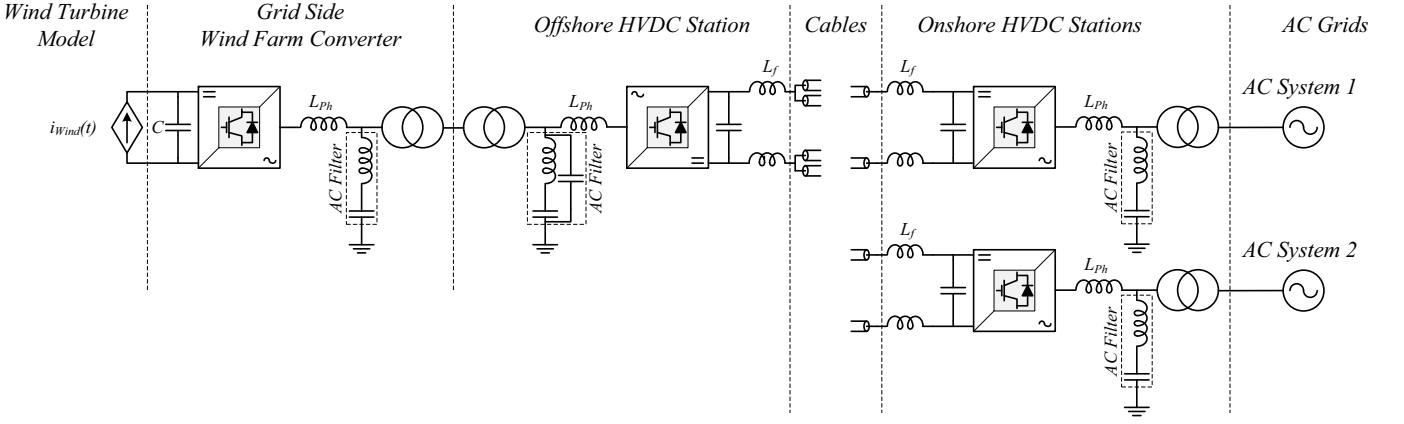


Fig. 1. Single line block diagram of a multiterminal VSC-HVDC connection.

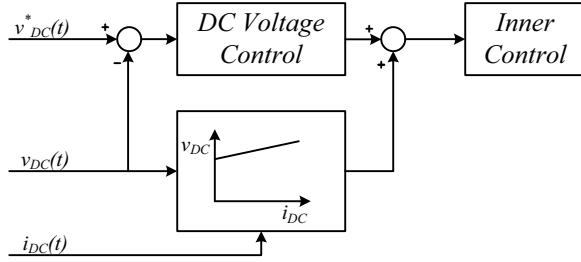


Fig. 2. DC droop characteristics for multiterminal connection control.

A. Scheduled Power Control

This technique does not present a real closed loop control. It is based in a schedule determined by the transmission system operator from one of AC grids. For this case, the AC system number 2 is requiring 0.75pu from onshore station number 2.

For this reason, a current reference is set in order to deliver to the AC grid a amount of power which was planned.

B. DC Voltage Droop Control

The droop technique [23] aims to change the the DC voltage reference in each station according to a defined droop. An alternative droop technique can also be implemented adding to the current references signal the droop control. With this strategy it is also possible to keep the DC voltage at a constant set point. For this main reason, the DC voltage plus droop control will be adopted in this work. The block diagram for the droop control technique is presented in the Figure 2.

C. Central DC Voltage Control

This strategy is based on a central control coordination which has the information from each onshore station. Data such as currents and voltages in each stations are available and, according to the characteristics of the transmission line a DC voltage set point is adopted [22]. The main block diagram for this control strategy is presented in the Figure 3

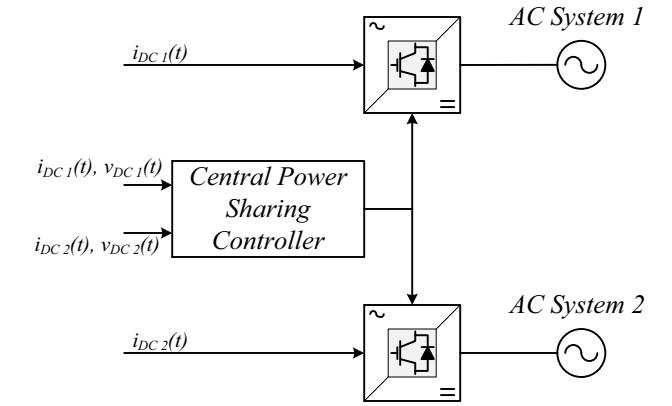


Fig. 3. Central DC voltage control for power sharing.

V. SIMULATION RESULTS

A. Scheduled Power Control

The first case regards the scheduled control strategy which a defined power is imposed over the onshore converter on the onshore station 2. It is considered wind steps with 0.5pu of the rated wind farm power. The first step happens at 500 ms followed by another increasing step with the other half of power. After 100ms, the wind decreases to 0.5pu. Figure 4 illustrates the simulation results for this case.

1) *Wind Farm Results:* The first wave form presented by the Figure 4 is related with the AC voltage measured over the AC filter. The currents, which are presented in the second frame, are the currents in the output of the transformer and going to the primary of the transformer. The DC voltage appears in the last frame. All graphs are rated in 1.50pu.

The same procedure is going to be presented by all the simulation results. For the other two strategies, the performance of the wind farm converters are very close to the results presented in this subsection. Due to that, the results for the next section are going to present just the simulation results about the HVDC converters.

2) *Offshore Converter Results:* For the offshore converter, which is responsible to control the AC voltages, the simulations results are presented in the Figure 5.

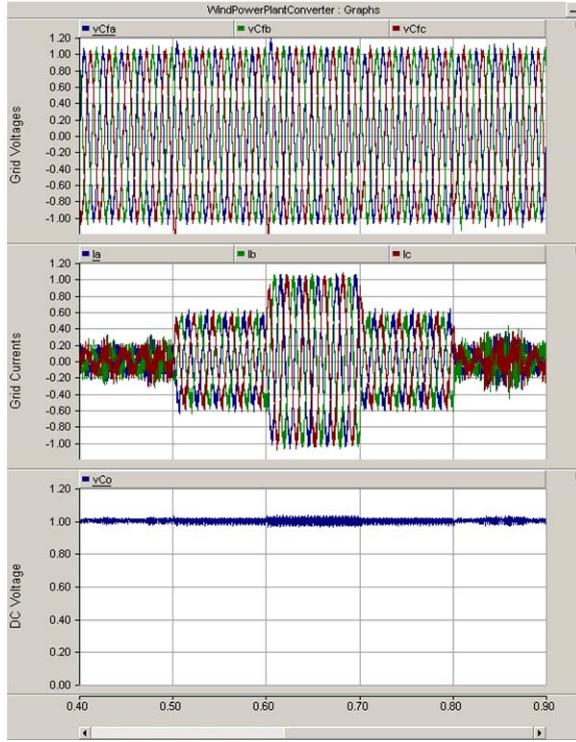


Fig. 4. Wind farm simulation results using Scheduled Power Control.

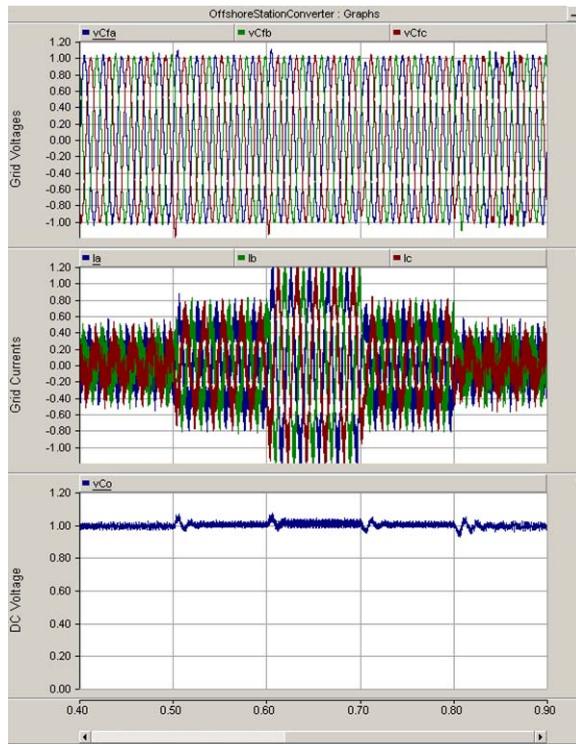


Fig. 5. Offshore station simulation results using Scheduled Power Control.

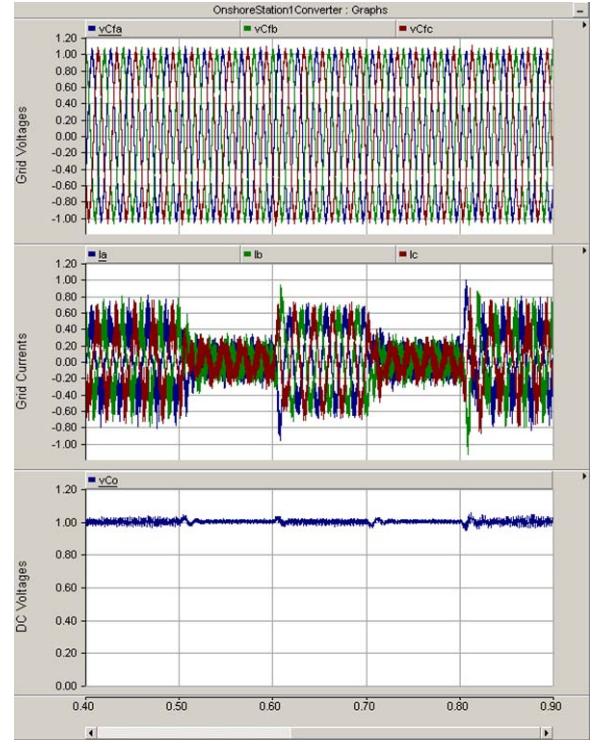


Fig. 6. Onshore station 1 simulation results using Scheduled Power Control.

For this case, the control is able to keep the AC voltages in the rated values. However, due to the absence of DC voltage controller, there is a strong transient in the DC voltage compared with the wind farm case.

3) Onshore Station 1 Results: The results for the onshore converter which presents the DC voltage regulation is showed in the Figure 6.

Due to the transient presented in the offshore side, this converter is directly influenced since that the AC currents need to change in order to keep the DC voltage constant, as it desired. It needs to be emphasized that before the energy from the wind comes from offshore side, the power required by the second onshore converter is delivered by this station.

4) Onshore Station 2 Results: This case presents a very stable case for the AC side. The currents present a constant value during all the time period. From the beginning, the onshore station 1 supplies the energy required by this converter. After that, the energy comes from the offshore side. Analysing the wave forms presented in the Figure 6 and 7 is possible to observe this behaviour.

B. DC Voltage Droop Control

The same condition was used in this control scheme. However, both onshore stations are equipped with DC voltage control and droop curve is added to guarantee the sharing. The droop was determined by the relationship between the resistances of each cable.

1) Offshore Converter Results: The offshore station, again, presents smaller transient in the DC voltage. The AC voltages are regulated at a set point. Simulations results presented in the Figure 8.

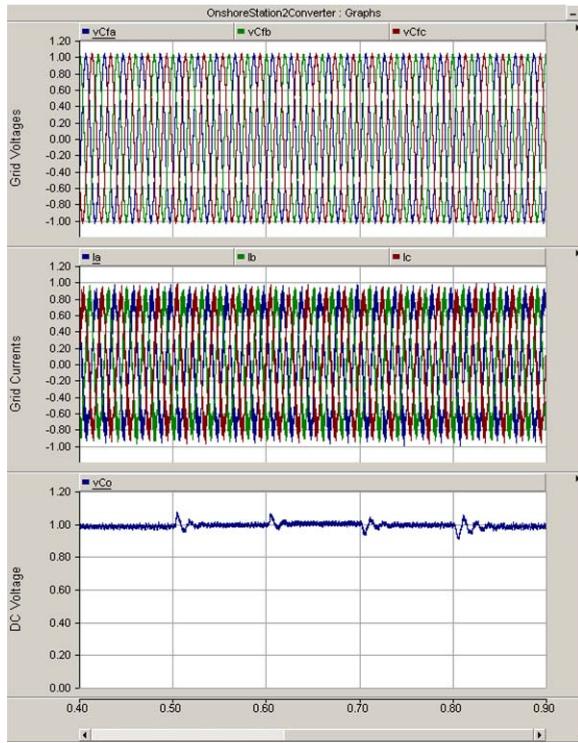


Fig. 7. Onshore station 2 simulation results using Scheduled Power Control.

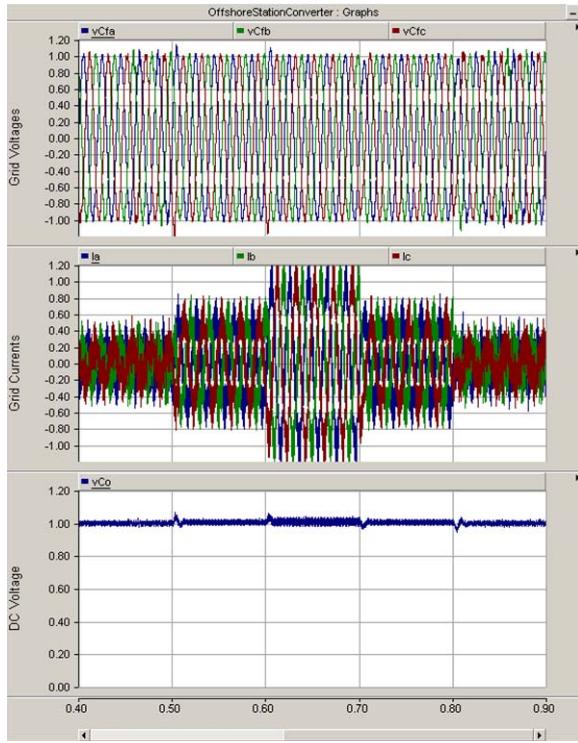


Fig. 8. Offshore station simulation results using DC Voltage Droop Control.

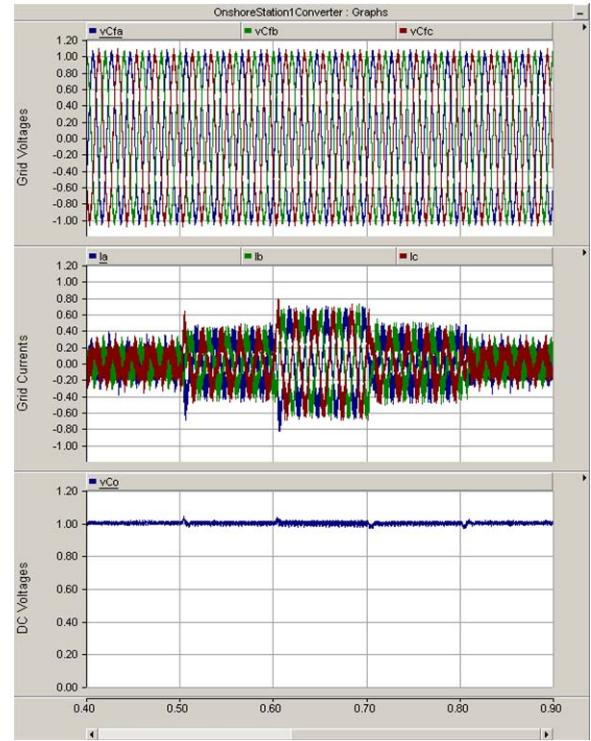


Fig. 9. Onshore station 1 simulation results using DC Voltage Droop Control.

2) *Onshore Station 1 Results:* The results for the onshore converter 1 is showed in the Figure 9.

For this the DC voltage presents smaller transients compared with the previous case since that the DC bus is also regulated by another converter.

3) *Onshore Station 2 Results:* This station now suffers the transient in the AC currents with are delivered to grid. However, due to the DC voltage control the DC bus presents a better response. The response is given in the Figure 10

Another characteristic of this system is the automatic share about the power which is processed by each onshore converter. For this, both converters are able to process a defined amount of power.

C. Central DC Voltage Control

The last strategy is based on the studies presented on ???. Similar to the previous case, the DC voltage reference changes according to processed current of each converter. Also, the line impedance is considered.

1) *Offshore Converter Results:* The AC voltages are again regulated for this case. The power is delivered to both onshore stations with transients during changes in the wind power. The wave forms are illustrated in the Figure 11.

2) *Onshore Station 1 Results:* With some differences in the transients compared with the case presented above, Figure 12 shows the time domain simulation for onshore station 1.

3) *Onshore Station Results:* For the second onshore station, which presents half part of rated power, Figure 13 shows the simulations results using central power controller.

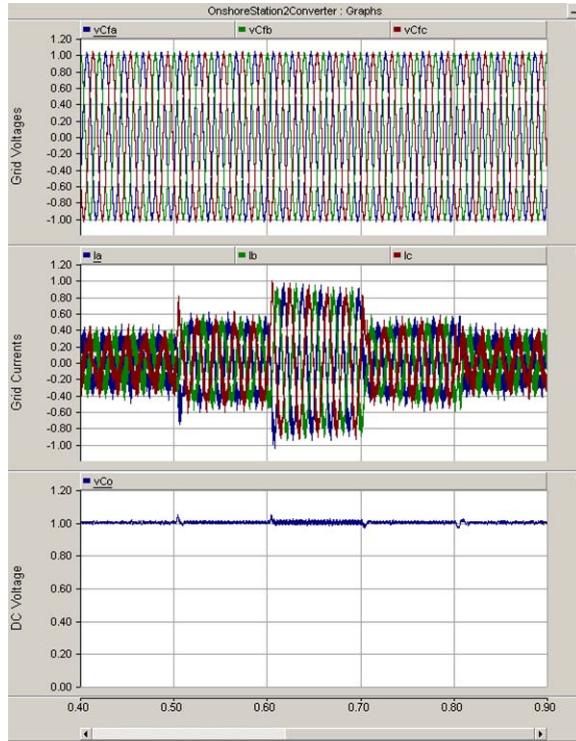


Fig. 10. Onshore station 2 simulation results using DC Voltage Droop Control.

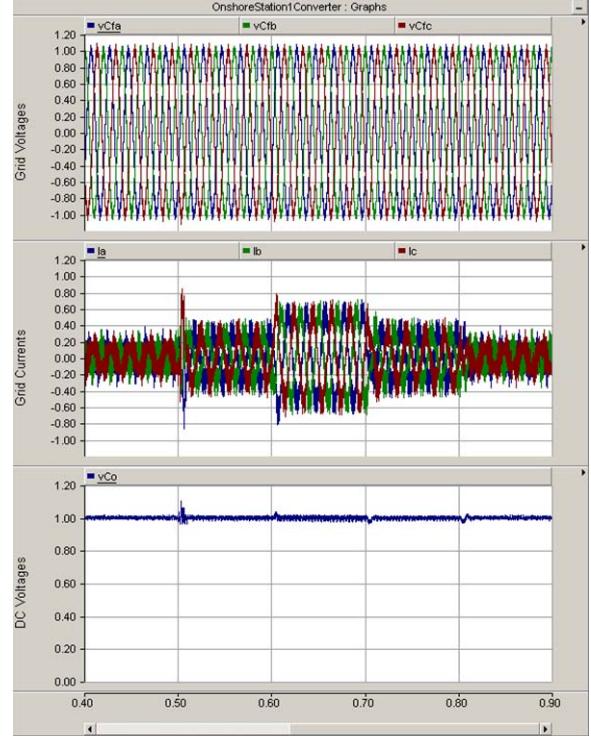


Fig. 12. Onshore station 2 simulation results using Central DC Voltage Control.

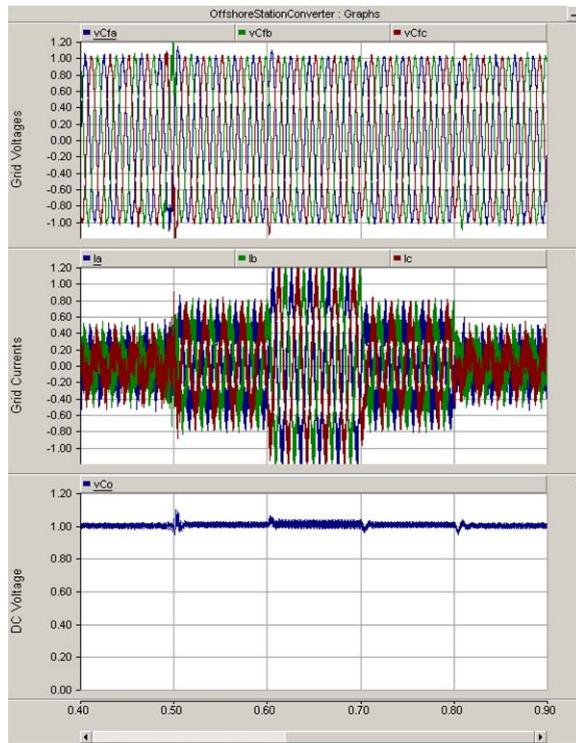


Fig. 11. Offshore station simulation results using Central DC Voltage Control.

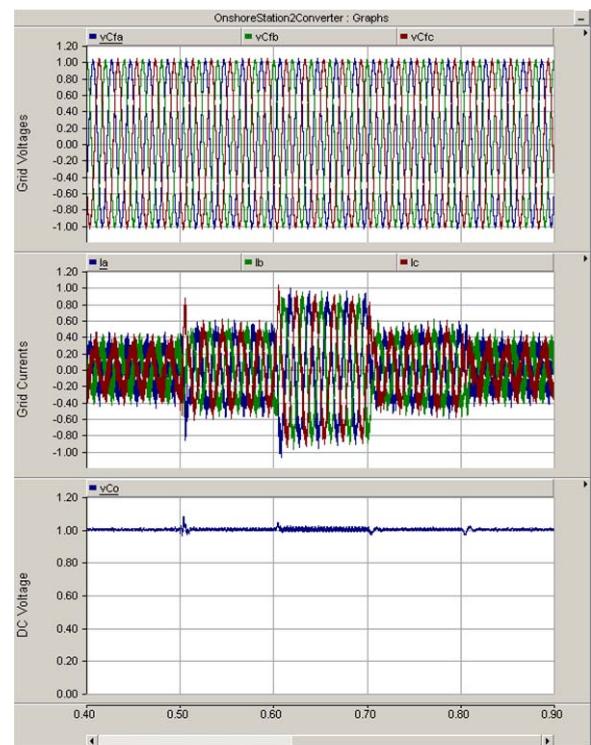


Fig. 13. Onshore station 2 simulation results using Central DC Voltage Control.

VI. DISCUSSIONS

A comparison among three control strategies used in multiterminal VSC-HVDC connection were referenced and time domain simulation was provided. EMTDC-PSCAD platform was used as simulation tool.

The first strategy showed a easy scheme based on a scheduled power delivery. However, the DC link presented bad transient behaviour in the offshore side as in the onshore station 2. The droop control was also presented and the simulation results showed that the DC link is kept constant and the transients are better compared with the previous case. Also the last strategy control presented good transients during the wind variations. However the currents, for the last two cases, presented transients since that, the references for the currents are provided by the outer control loops which present variations due to the variation in the DC voltage and DC currents.

REFERENCES

- [1] R. Gelman and S. Hockett, "2008 renewable energy data book," tech. rep., U. S. Department of Energy, July 2009.
- [2] L. H. Hansen, L. Helle, F. Blaabjerg, E. Ritchie, S. Nielsen, H. Bindner, P. Srensen, and B. Bak-J, "Conceptual survey of generators and power electronics for wind turbines," tech. rep., Ris National Laboratory, December 2001.
- [3] V. J. Sood, *HVDC and FACTS Controllers Applications of Static Converters in Power Systems*. Kluwer Academic Publishers, 2004.
- [4] M. P. Bahrman, "Overview of hvdc transmission," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, pp. 18–23, 29 2006-Nov. 1 2006.
- [5] V. Lescale, A. Kumar, L.-E. Juhlin, H. Bjorklund, and K. Nyberg, "Challenges with multi-terminal uhvdc transmissions," in *Power System Technology and IEEE Power India Conference, 2008. POWERCON 2008. Joint International Conference*, pp. 1–7, October. 2008.
- [6] H. Chen, F. Zhang, and Y. Chang, "Improvement of power quality by vsc based multi-terminal hvdc," in *Power Engineering Society General Meeting, 2006. IEEE*, p. 6 pp., 0-0 2006.
- [7] W. Lu and B.-T. Ooi, "Premium quality power park based on multi-terminal hvdc," *Power Delivery, IEEE Transactions on*, vol. 20, pp. 978–983, April 2005.
- [8] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *Industry Applications, IEEE Transactions on*, vol. IA-20, pp. 625–630, May 1984.
- [9] H. Akagi, S. Ogasawara, and H. Kim, "The theory of instantaneous power in three-phase four-wire systems: a comprehensive approach," in *Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE*, vol. 1, pp. 431–439 vol.1, 1999.
- [10] T. Rachmildha, A. Llor, M. Fadel, P. Dahono, and Y. Haroen, "Hybrid direct power control using p-q-r power theory applied on 3-phase 4-wire active power filter," in *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*, pp. 1183–1189, June 2008.
- [11] L. Czarnecki, "On some misinterpretations of the instantaneous reactive power p-q theory," *Power Electronics, IEEE Transactions on*, vol. 19, pp. 828–836, May 2004.
- [12] C. Du, A. Sannino, and M. H. J. Bollen, "Analysis of response of vsc-based hvdc to unbalanced faults with different control systems," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, pp. 1–6, 2005.
- [13] C. Du, A. Sannino, and M. H. J. Bollen, "Analysis of the control algorithms of voltage-source converter hvdc," in *Power Tech, 2005 IEEE Russia*, pp. 1–7, June 2005.
- [14] X. Wei and G. Tang, "Analysis and control vsc-hvdc under unbalanced ac conditions," in *Power System Technology, 2006. PowerCon 2006. International Conference*, pp. 1–5, Oct. 2006.
- [15] K. R. Padiyar and N. Prabhu, "Modelling, control design and analysis of vsc based hvdc transmission systems," in *Power System Technology, 2004. PowerCon 2004. 2004 International Conference*, vol. 1, pp. 774–779 Vol.1, November 2004.
- [16] A. Tyagi and K. Padiyar, "Dynamic analysis and simulation of a vsc based back-to-back hvdc link," in *Power Electronics, 2006. IICPE 2006. India International Conference*, pp. 232–238, December 2006.
- [17] M. Durrant, H. Werner, and K. Abbott, "Model of a vsc hvdc terminal attached to a weak ac system," in *Control Applications, 2003. CCA 2003. Proceedings of 2003 IEEE Conference*, vol. 1, pp. 178–182 vol.1, June 2003.
- [18] C. Guo and C. Zhao, "A new technology for hvdc start-up and operation using vsc-hvdc system," in *Power Energy Society General Meeting, 2009. PES '09. IEEE*, pp. 1–5, July 2009.
- [19] C. Du and M. Bollen, "Power-frequency control for vsc-hvdc during island operation," in *AC and DC Power Transmission, 2006. ACDC 2006. The 8th IEE International Conference*, pp. 177–181, March 2006.
- [20] S. Ruihua, Z. Chao, L. Ruomei, and Z. Xiaoxin, "Vscs based hvdc and its control strategy," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, pp. 1–6, 2005.
- [21] M. Delghavi and A. Yazdani, "A control strategy for islanded operation of a distributed resource (dr) unit," in *Power Energy Society General Meeting, 2009. PES '09. IEEE*, pp. 1–8, 26-30 2009.
- [22] A. Agap and C. M. Dragan, "Multiterminal dc connection for offshore wind farms," Master's thesis, Aalborg University, 2009.
- [23] L. Xu, L. Yao, and M. Bazargan, "Dc grid management of a multi-terminal hvdc transmission system for large offshore wind farms," in *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference on*, pp. 1–7, 6-7 2009.

Rodrigo da Silva was Born in Brazil. He received his Bachelors and Masters degrees from Federal University of Santa Catarina, Brazil in 2007 and 2009, all in electrical engineering. Since 2009, he is a PhD student at Aalborg University, Denmark.

Remus Teodorescu received the Dipl.Ing. degree in electrical engineering from Polytechnical University of Bucharest, Romania in 1989, and PhD. degree in power electronics from University of Galati, Romania, in 1994. In 1998, he joined Aalborg University, Department of Energy Technology, power electronics section where he currently works as full professor. He is the co-recipient of the Technical Committee Prize Paper Awards at IEEE IAS Annual Meeting 1998, and Third-ABB Prize Paper Award at IEEE Optim 2002. He is a Senior Member of IEEE, Associate Editor for IEEE Power Electronics Letters and chair of IEEE Danish joint IES/PELS/IAS chapter. His areas of interests are: design and control of power converters used in renewable energy systems, distributed generation mainly wind power and photo-voltaics, computer simulations, digital control implementation.

Remus Teodorescu is the founder and coordinator of the Green Power Laboratory at Aalborg University focusing on the development and testing of grid converters for renewable energy systems and the coordinator of the Vestas Power Program.

Pedro Rodriguez (S'99-M'04) received the M.S. and Ph.D. degrees in electrical engineering from the Technical University of Catalonia (UPC), Barcelona, Spain, in 1994 and 2004, respectively. In 1990, he joined the faculty of UPC as an Assistant Professor, where he is currently an Associate Professor. In 2005, he was a visiting researcher in the Center for Power Electronics Systems, Virginia Tech, USA. In 2006 and 2007, he was a Post-doc researcher in the Institute of Energy Technology, Aalborg University (AAU), Denmark, where he lectures Ph.D. courses from 2006. He is now the Head of the Research Group on Renewable Electrical Energy Systems at the UPC and co-Supervisor of the Vestas Power Programme in partnership collaboration with the AAU. He has coauthored about 100 papers in technical journals and conferences. He is the holder of four patents. His research interest is focused on applying power electronics to distributed energy systems and power quality.

Dr. Rodriguez is a Member of the IEEE Power Electronics, IEEE Industry Application, and IEEE Industrial Electronics Societies. In this last society he has been active organizing several special sessions in conferences on the control of distributed energy systems based on renewable energies and presenting several tutorials. Currently, he is a member of the IEEE IES Technical Committee on Renewable Energy Systems and the chair of the IEEE Industrial Electronics Student Forum.