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Review on Hybrid HVDC Technology for Integration of Offshore Wind Power Plant

Chunming Yuan, Xiaobo Yang, Dawei Yao, Chengyan Yue
Corporate Research Center
ABB (China) Limited
Beijing, China
Chunming.yuan@cn.abb.com

***Abstract*— VSC HVDC will be the most important approach for transmitting the power of large-scale offshore wind power plant in the near future. In recent literature, the feasibility of using hybrid type HVDC for offshore wind transmission has been discussed. A hybrid HVDC system has at one line commutated converter (LCC) at mainland and one voltage source converter (VSC) at offshore platform, which may inherit advantages of both LCC and VSC. It is possible to connect more VSCs at offshore platforms or LCC at onshore stations to the HVDC system to form a hybrid multiterminal system (MTDC). The purpose of this paper is to review the hybrid HVDC/MTDC technologies for offshore wind power plant connections reported in recent literature. Three types of hybrid HVDC topologies, i.e. VSC-LCC hybrid HVDC, VSC tapping LCC HVDC and hybrid CSC HVDC are presented. Based on the summary of the literature, the challenges of hybrid HVDC for offshore wind power plant integration are identified and further research works are proposed.**

Keywords- HVDC; Wind power plant; VSC; CSC

I. INTRODUCTION

Offshore wind power has been developing rapidly in the world in recent years. By 2020, EWEA targets to develop 40 GW installed capacity for offshore wind in Europe, equivalent to 4% EU electric power demand [1]. In China, it is estimated that offshore wind power will reach 30 GW by the end of 2020 [2].

Offshore wind power plants collect power with tens or even hundreds of wind turbines while the total capacity could be several hundred MW. Cable system is necessary to transmit the wind power to the AC grid at main land. Most of early offshore wind power plant had been connected to mainland with submarine AC cables as the location of wind power plants are close to the coast. However, when the offshore wind power plant trends to be located further away from the coast , the drawback of the HVAC transmission is uncovered [3]. For example, the BARD Offshore 1 (BorWin 1) wind power plant, with total capacity of 400MW, is located about 125km from the coast in the North Sea. The use of AC cable is not recommended due to huge power losses introduced by charging current.

Systems based on High Voltage Direct Current transmission (HVDC) is a preferred solution for offshore wind power transmission, which offers lower power losses than AC cable connection for large offshore wind power plant with long distance to the mainland grid. By far, there are two alternative mature types of HVDC technology available: LCC HVDC using thyristor based converter, and voltage source converter (VSC) HVDC using IGBT based converters.

LCC HVDC technology has been operated with high reliability and little maintenance for more than 40 years. It is possible to employ LCC HVDC for offshore wind power connection[4] [5, 6]. However, reactive power compensation devices with approximate 40% rated active power is required and a synchronous condenser is also needed to provide commutation voltage for LCC. As alternative of synchronous condenser, static synchronous compensator (StatCom) can be also used for offshore LCC, which has much faster control and lower losses. Additionally, StatCom can also provide reactive power for LCC. However, a complicated coordination control among wind turbines, StatCom and HVDC station is necessary to carry out the balance of active and reactive power among three devices [6, 7]. More importantly, LCC has large footprint and is difficult to be installed at an offshore platform.

VSC HVDC has several advantages over conventional LCC HVDC in offshore applications [3, 8]. It has more compact architecture and less weight, which are important characteristics for offshore platform design and construction. Furthermore, it has independent active/reactive power control and islanding operation capability, which is important for start-up of offshore wind power plant. Therefore, all the offshore wind power plant HVDC transmission projects commissioned or under construction have adopted the VSC HVDC scheme, one example is the 400 MW BorWin1 delivered by ABB in 2012 [9].

To consider correlating technologies of both VSC HVDC and LCC HVDC, the hybrid HVDC technology was proposed. A hybrid HVDC system consists of one VSC and one LCC at least. For offshore wind connection, the VSC terminal is located at offshore platform and the LCC terminal is located onshore. The advantages of Hybrid

HVDC include: Lower losses compared with VSC HVDC, and more suitable for offshore platform than LCC HVDC. Besides, hybrid HVDC decreases the requirement on DC circuit breakers as the DC power is unidirectional and only unidirectional breaker on sending end is needed[10].

First study concerning hybrid HVDC was found in 1992[11], based on GTO type VSC. Since that, research works of hybrid HVDC system has been widely developed, including the fundamental principle and topology, the equivalent model, control & protection, application, reliability evaluation and etc. However, the application of hybrid HVDC for offshore wind power connection was not discussed until recent years. In 2006, the hybrid MTDC system was proposed for offshore wind connection, in which VSCs are adopted at wind turbine terminals and LCC is utilized at AC grid terminal[12]. Since 2009, various control methods for two terminal hybrid HVDC systems were proposed [13-17].

Besides the VSC-LCC topology (VSC for offshore grid and LCC for onshore grid), there are other hybrid HVDC systems proposed for offshore wind connections: In [18], a hybrid HVDC system with the current source converter using full control device and PWM modulation method (PWMCSC) is proposed, in which the PWMCSC is placed offshore and an LCC is placed onshore. PWMCSC can mitigate the DC fault, improve the performance of LCC during AC fault and have self-start capability [19]. Besides, another hybrid HVDC system with LCC at offshore while PWMCSC at onshore was also proposed for offshore wind power plant connection [20, 21]. In [22], a hybrid converter station consists of twelve-pulse diode rectifier and a VSC was introduced for offshore side connection, while another VSC is employed for onshore AC grid connection. Recent years, hybrid MTDC system for offshore wind power plant connection was also discussed, in which the VSC station is connected to offshore wind power plant and feed the power to an LCC HVDC system [23] or a hybrid MTDC system[24]. Another hybrid HVDC tapping system is proposed in [16], in which the offshore wind power plant is connected with diode rectifier and feed into VSC HVDC or LCC HVDC.

The main limitation of hybrid HVDC systems is that it cannot reverse the power flow quickly due to the DC voltage polarity of LCC need to be changed. The reverse of hybrid of the power flow in the hybrid system may need additional mechanical operation and discharge of the DC link [13]. However, the power flow revers is not necessary for offshore wind power plant during steady state as the power is always flow from offshore to shore. Another limitation is from LCC converter station when a weak AC grid is connected at onshore when LCC has higher commutation failure risk. Capacitor commutate converter (CCC) is proposed to replace the LCC in [13]. The LCC at AC grid terminal can also be replaced by a PWM current source converter (PWMCSC) to increase the reliability of the converter station [20, 21].

The start-up of VSC-LCC hybrid HVDC for offshore wind power plant is a critical issue because usually the offshore ac grid is provided by VSC, for which the DC voltage should be setup in advance. However, the DC voltage cannot be provided by LCC due to its unidirectional current characteristic. Several literatures had discussed this issue and proposed various solutions such as reverse polarity of LCC [15] and additional LCC rectifier [16].

This paper will focus on the overview of hybrid HVDC technologies for integration of offshore wind power plant. Three types of hybrid HVDC will be reviewed: 1) VSC-LCC hybrid HVDC; 2) VSC tapping from LCC HVDC and 3) Hybrid CSC HVDC. The pros and cons of hybrid HVDC for offshore wind power application will be analyzed and summarized.

II. TOPOLOGIES OF VSC-LCC HYBRID HVDC SYSTEMS

The hybrid two-terminal transmission technology has been discussed and studied for more than twenty years. According to the locations of the converters, two topologies exist: LCC-VSC (LCC as rectifier while VSC as inverter), and VSC-LCC (VSC as rectifier while LCC as inverter). The first topology is mainly studied and discussed in the early stage [11, 25-29], because the VSC as inverter eliminates the risk of commutation failure essentially and enhances the reliability of the whole HVDC system. It can also afford a low cost scheme for the application of passive network [29].

However, the second topology VSC-LCC was not studied much until the offshore wind being addressed as important wind power source, due to lower losses compared with VSC HVDC, less size and more control flexibility compared with of LCC HVDC.

A. Structure

A typical configuration of VSC-LCC HVDC for offshore wind power plant is shown in the Fig 1. It comprises four parts: offshore wind power plant, offshore VSC station platform, onshore LCC station and DC submarine cable between the two stations. The VSC station is placed on the offshore platform operates as a rectifier; a twelve-pulse LCC inverter station receives the DC power from VSC via the submarine dc cable. The ac side of LCC station connects to the onshore AC grid.

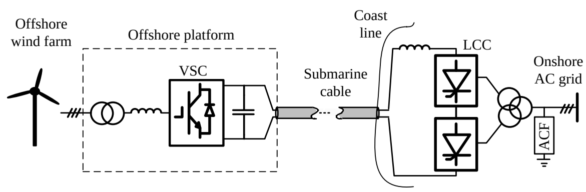

Figure 1. VSC-LCC hybrid HVDC for offshore wind power plant

In order to transmit maximum power from wind turbines and reduce the total cost of wind power plant and HVDC system, a multiVSC-LCC hybrid MTDC system was proposed [12]. At the offshore side, the wind turbines are controlled by VSCs to track the max wind power at different wind power plants with variation of wind velocity. At the onshore AC grid, an LCC is used to invert the aggregated power into AC grid.

B. Control

In the early studies, the normal control method for hybrid HVDC was proposed, in which the LCC employed conventional fix extinction angle control or constant voltage control; VSC employed active power/reactive power control, including rotating reference frame [13], directive power control [14]. However, in these preliminary studies, an AC bus was assumed at offshore wind power plant, which is not adequate as at present all the commercial wind turbine generators only control active power and reactive power. The AC voltage and frequency of offshore wind power plant should be established by VSC. The active power generated by the offshore wind turbines as well as the total reactive power generated in offshore wind power plant will be absorbed by VSC automatically.

A simple controller for VSC was shown in [15], in which the AC voltage is controlled on the d-q rotating frame. In the outer voltage loops, the d voltage axis is set to rated value while q axis voltage is set to 0. Inner current controllers are employed to realize better control performance.

The frequency of AC voltage can be also controlled with a closed loop, which provides the possibility of load-frequency control of offshore wind power plant[30]. In [16], a proportional controller is used for frequency control of offshore VSC.

C. Challenges

Firstly, the hybrid HVDC cannot realize on-line power flow reverse [11]. Although the power flow reverse is not necessary for offshore wind power plant during steady state as the power is always flow from offshore to shore, it results in the difficulty of start-up of offshore wind power plant. To set up the AC voltage of offshore wind power plant, the DC voltage of offshore VSC is needed, which cannot be provided by LCC inverter at onshore grid. One solution is to reverse polarity of LCC before connection of wind turbines [15]. Firstly, the offshore VSC's DC capacitors are charged through grid side LCC with reversed polarity (rectifier mode). After the capacitors of VSC is charged, the LCC is switched to normal inverter mode and then the wind turbines are connected to the VSC while the LCC is de-blocked. Another solution was proposed in [16], in which an auxiliary LCC rectifier is employed to provide the starting energy and setup initial DC voltage. When the system operates normally, the auxiliary rectifier LCC will be blocked. Obviously, the additional charging rectifier will increase the total costs of the system.

Secondly, the commutation failure in LCC inverter has serious impact on the hybrid HVDC system, in particular on the VSC converter. Once a commutation failure happens at LCC side, VSC converter will experience a DC short circuit viaLCC. The short circuit current is supplied by the anti-parallel diodes of VSC [31] and increases rapidly, which results in slow recovery of commutation failure of LCC inverter [16]. To mitigate this problem, a capacitor commutated converter (CCC) is proposed to replace the LCC station in this kind of application [13, 16].

Finally, the natural characteristic of wind power variation may cause reactive power and voltage fluctuation at onshore AC grid. The reactive power compensation devices at LCC may be not enough. In this case of weak onshore AC grid, additional reactive compensation such as SVC or StatCom is needed.

III. Hybrid HVDC using Full Controlled Device Based Current Source Converter

Recently, a full-controlled device based PWM current source converter (PWMCSC) was investigated as an alternative solution of VSC based hybrid HVDC [18, 32-34]. PWMCSC employs full-controlled device, such as IGBT or IGCT. As devices inside PWMCSC are reverse block type, it avoids the DC short circuit issue during DC fault or commutation failure of LCC.

A. Structure

The hybrid topology combined with PWMCSC and LCC can be also applied for offshore wind power plant connection. Because the PWMCSC and LCC are both and current sourced converters, the coupling between them is easier than VSC-LCC hybrid systems [19]. At present, there are two type of hybrid HVDC system combined with PWMCSC and LCC in terms of the converter locations. One type is PWMCSC-LCC, in which the PWMCSC rectifier located at offshore wind power plant while LCC inverter connects to on shore AC grid [18, 19]. Another type is LCC-PWMCSC, in which the LCC rectifier is located offshore while PWMCSC located onshore. The simplified diagrams of these two solutions are depicted in Fig 2 and Fig 3 respectively.

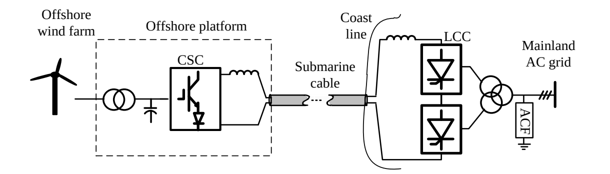

Figure 2. PWMCSC-LCC HVDC for offshore wind power plant

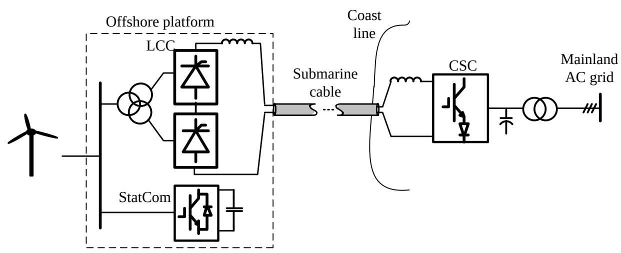

Figure 3. LCC-PWMCSC HVDC for offshore wind power plant

B. Control of PWMCSC-LCC

Different from traditional LCC HVDC, it was recommended that the LCC inverter in the PWMCSC-LCC HVDC controls DC current instead of constant extinction angle during normal operation to provide constant DC current for PWMCSC. The PWMCSC regulates the AC voltage and frequency of offshore grid. A control diagram is presented in [19], in which the AC voltage is controlled directly by a single control loop with feed forward signals of offshore wind current and derivative of reference voltage.

The start-up of PWMCSC-LCC HVDC system would be straight forward as the LCC can control the DC current at the beginning and energize the PWMCSC simultaneously. When the DC current reaches the nominal value, PWMCSC is enabled and setup the AC voltage in island mode. Finally, offshore wind power plant is enabled and started normal generation operation.

C. Control of LCC-PWMCSC

Another application for the topology is to use LCC for offshore wind power plant connection and PWMCSC for onshore AC grid connection [20, 21, 33]. An additional StatCom is need at LCC side to provide commutation voltage. The overall control of the hybrid system can be divided into three parts [33]: the StatCom regulates the AC bus voltage of offshore wind power plant, the offshore LCC rectifier tracks and transmits the wind power; the onshore PWMCSC receives and delivers the active power to the grid. To maintain the power balance between offshore wind power plant and LCC rectifier, the DC link voltage of StatCom is employed as control objective as it will vary when active balance is broken.

To realize the start-up of LCC-PWMCSC system, a diesel generator may be necessary to energize the StatCom at first to establish the offshore AC grid. Then the HVDC and offshore wind power plant can be enabled and start normal operation in sequence.

The LCC-PWMCSC system avoids commutation failure at inverter side thus total reliability is higher than an LCC HVDC system with StatCom. However, obvious advantages are not foreseen as the large footprint of LCC together with StatCom will become the main limitation for offshore platform application.

D. Challenges

One limitation of PWMCSC based hybrid HVDC is when the DC current is maintained at nominal value even under low wind conditions, which increase the total losses. One solution to overcome this issue is to reduce DC current reference at low wind conditions.

Besides, PWMCSC requires semiconductors with reverse blocking capability. Before a commercialized PWMCSC for HVDC application, several issues need to be solved such as reducing power losses and developing topology for high voltage application.

IV. VSC TAPPING FROM LCC HVDC

VSC tapping from LCC HVDC is the configuration connecting a small VSC station to an LCC HVDC system. Generally, VSC tapping system will supply of power to the areas with relatively small consumption along the transmission corridor. Many literature had discussed this hybrid tapping MTDC system, such as the feasibility study [11, 35, 36], performance analysis [35, 37-39], control method [35, 37], applications [40], as well as reliability evaluation[41, 42]. Today, the hybrid tapping MTDC system could be also possible for rectifier operation so that distributed energy sources in the vicinity of the HVDC line can be picked up onto the grid system [11]. In recently years, the feasibility of using a VSC tapping station for offshore wind power connection to feed into LCC-HVDC transmission was investigated [23, 43]. Such a VSC tapping system brings several advantages for offshore wind transmission application. If the VSC station located on offshore can be connected into an existent LCC transmission line, the problem of VSC and offshore wind power plant start-up is solved naturally. As no additional equipment on shore is needed, the total investment can be reduced. Additionally, the intermittent of wind power can be compensated by the LCC rectifier to increase the AC grid stability at LCC inverter side.

A. Structure

Fig 4 depicts a simplified configuration of the VSC tapping from LCC HVDC for offshore wind power plant. The offshore parts are same with that of VSC-LCC hybrid HVDC. The difference is the onshore terminal where submarine cable connects on the transmission line of the LCC HVDC system directly.

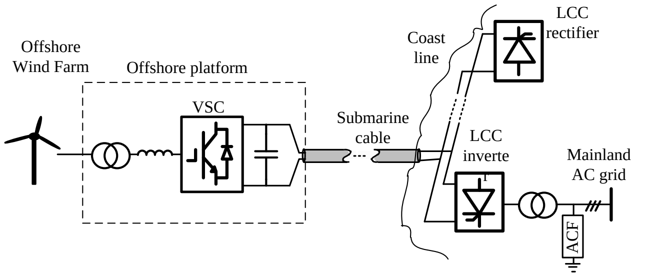

Figure 4. VSC tapping from LCC HVDC for offshore wind power plant

B. Control

In the hybrid tapping system, the control of LCC HVDC can employ conventional method, i.e. constant extinction angle control or constant voltage control for LCC rectifier and constant DC current control for LCC rectifier. The current reference of LCC rectifier can be adjusted based on the measurement of the DC current form offshore wind power plant as proposed in [23], to obtain constant power at LCC inverter side. Similar to hybrid HVDC system, the VSC will control the AC voltage and frequency for offshore wind power plant.

As the LCC rectifier can provide DC voltage support for VSC, the start of the offshore taping system is easier than that for a hybrid HVDC system. At First the offshore VSC is blocked while the LCC HVDC is started with conventional way. After the DC voltage is setup, VSC is de-blocked and offshore wind power plant starts normal operation.

C. Challenges

Similar to hybrid HVDC, a commutation failure at LCC inverter is reported to result in DC voltage collapse and uncontrollable DC short circuit current flows through the anti-parallel diodes of VSC. The DC short circuit current may damage the diodes and prolong the recovery time of the whole system after the AC fault. Compared with the AC faults at LCC inverter, the AC faults at LCC rectifier may be not a critical issue. The system can be recovered quickly without DC overcurrent.

V. CONCLUSIONS

Hybrid DC grid may benefit from the advantages of LCC and VSC technologies, and is among the solutions for offshore wind power plant connection.

Three types of hybrid HVDC technology have been reviewed for the application of connecting offshore wind power plant. It is summarized that:

- The basic control strategies of VSC or LCC station are still applicable for hybrid HVDC system.
- Black start of offshore wind power plant and commutation failure of LCC inverter station are among the main problems for the VSC based hybrid HVDC;

- The hybrid PWMCSC-LCC HVDC is attractive as it has faster recovery speed after AC faults at onshore AC gird, whereas further researches are needed on efficiency and high voltage topologies.

REFERENCES

[1] EWEA, http://www.ewea.org/policy-issues/offshore/.

[2] Xu, QY, et al., A discussion on offshore wind power output characteristics and its accommodation. Automation of Electric Power Systems, 2011(22): p. 54-59.

[3] Erik Koldby, M.H., Challenges on the road to an offshore HVDC grid. Nordic Wind Power Conference 2009, Bornholm, Denmmark, 2009.

[4] Xu, L. and B.R. Andersen, Grid Connection of Large Offshore Wind Farms Using HVDC. WIND ENERGY, 2006(9): p. 371-382.

[5] Kirby, N.M., et al., HVDC transmission for large offshore wind power plants. Power Engineering Journal, 2002. 16(3): p. 135-141.

[6] Bozhko, S., et al. Control of Offshore DFIG-based Wind Farm Grid with Line-Commutated HVDC Connection. in Power Electronics and Motion Control Conference, 2006. EPE-PEMC 2006. 12th International. 2006.

[7] Montilla-Djesus, M.E., et al., Optimal Operation of Offshore Wind Farms With Line-Commutated HVDC Link Connection. Energy Conversion, IEEE Transactions on, 2010. 25(2): p. 504-513.

[8] ABB, HVDC light: It's time to connect. www.abb.com/hvdc, 2012.

[9] ABB, Grid connection of offshore wind power plants - BorWin1. www.abb.com/hvdc.

[10] Vrana, T.K., D. Huertas-Hernando, and O.B. Fosso. Benefits of asymmetric HVDC links for large scale offshore wind integration. in Power and Energy Society General Meeting, 2012 IEEE. 2012.

[11] Zhao, Z., HVDC Application of GTO Voltage Source Inverters. 1992, University of Toronto. University of Toronto, Canada: Toronto, 1992.

[12] Wulue, P., C. Yong, and C. Hairong. Hybrid Multi-terminal HVDC System for Large Scale Wind Power. in Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES. 2006.

[13] Torres-Olguin, R.E., M. Molinas, and T.M. Undeland. A model-based controller in rotating reference frame for Hybrid HVDC. in Energy Conversion Congress and Exposition (ECCE), 2010 IEEE. 2010.

[14] Torres-Olguin, R.E., M. Molinas, and T. Undeland. A direct power control for Hybrid HVDC transmission systems. in PowerTech, 2011 IEEE Trondheim. 2011.

[15] Zhan, P., et al., Research on hybrid multi-terminal high voltage DC technology for offshore wind power plant integration Journal of Modern Power Systems and Clean Energy, 2013. 1(1): p. 32-39.

[16] Torres-Olguin, R.E., M. Molinas, and T. Undeland. Hybrid HVDC connection of large offshore wind power plants to the AC grid. in Industrial Electronics (ISIE), 2012 IEEE International Symposium on. 2012.

[17] Thi, M.S.-N. and L. Wang. Stability analysis of different offshore wind power plants feeding into a large power grid through a hybrid HVDC link. in Industrial Electronics (ISIE), 2013 IEEE International Symposium on. 2013.

[18] Torres-Olguin, R.E., et al. Integration of Offshore Wind Farm Using a Hybrid HVDC Transmission Composed by PWM Current-Source Converter and Line-Commutated Converter. in Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific. 2012.

[19] Torres-Olguin, R.E., et al., Integration of Offshore Wind Farm Using a Hybrid HVDC Transmission Composed by the PWM Current-Source Converter and Line-Commutated Converter. Energy Conversion, IEEE Transactions on, 2013. 28(1): p. 125-134.

[20] Honglin, Z., Y. Geng, and G. Hua. Grid integration of DFIG-based offshore wind power plants with hybrid HVDC connection. in ICEMS 2008. 2008.

[21] Honglin, Z. and Y. Geng. Control of DFIG-based wind power plants with hybrid HVDC connection. in Power Electronics and Motion Control Conference, 2009. IPEMC '09. IEEE 6th International. 2009.

[22] Thanh-Hai, N. and L. Dong-Choon. Control of offshore wind power plants based on HVDC. in Energy Conversion Congress and Exposition (ECCE), 2012 IEEE. 2012.

[23] Torres-Olguin, R.E., M. Molinas, and T. Undeland, Offshore Wind Farm Grid Integration by VSC Technology With LCC-Based HVDC Transmission. Sustainable Energy, IEEE Transactions on, 2012. 3(4): p. 899-907.

[24] Chen, X., et al., Integrating Wind Farm to the Grid Using Hybrid Multi-terminal HVDC Technology. Industry Applications, IEEE Transactions on, 2010. PP(99): p. 1-1.

[25] Zhao, Z. and M.R. Iravani, Application of GTO voltage source inverter in a hybrid HVDC link. Power Delivery, IEEE Transactions on, 1994. 9(1): p. 369-377.

[26] Iwatta, Y., et al. Simulation Study Of A Hybrid Hvdc System Composed Of A Self-commutated Converter And A Line-commutated Converter. in AC and DC Power Transmission, Sixth International Conference on (Conf. Publ. No. 423). 1996.

[27] Li, G., et al. Research on hybrid HVDC. in Power System Technology, 2004. PowerCon 2004. 2004 International Conference on. 2004.

[28] Torres-Olguin, R.E., M. Molinas, and T.M. Undeland. A controller in d-q synchronous reference frame for hybrid HVDC transmission system. in Power Electronics Conference (IPEC), 2010 International. 2010.

[29] Kotb, O. and V.K. Sood. A hybrid HVDC transmission system supplying a passive load. in Electric Power and Energy Conference (EPEC), 2010 IEEE. 2010.

[30] Jensen, S. and F.W.Fuchs, Load-Frequency Control of Synchronous Areas Using a Wind Farm Connected via HVDC-VSC, in 2nd EPE Wind Energy Seminar. 2009: KTH, Stockholm, Sweden

[31] Jin, Y., J.E. Fletcher, and J. O'Reilly, Short-Circuit and Ground Fault Analyses and Location in VSC-Based DC Network Cables. Industrial Electronics, IEEE Transactions on, 2012. 59(10): p. 3827-3837.

[32] Honglin, Z., Y. Geng, and G. Hua. Grid integration of DFIG-based offshore wind power plants with hybrid HVDC connection. in Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on. 2008.

[33] Honglin, Z., Y. Geng, and W. Jun, Modeling, Analysis, and Control for the Rectifier of Hybrid HVdc Systems for DFIG-Based Wind Farms. Energy Conversion, IEEE Transactions on, 2011. 26(1): p. 340-353.

[34] Xue YL, et al., Modeling and Simulation for a Hybrid Current Source Converter High Voltage Direct Current Transmission System. Automation of Electric Power systems, 2012(09): p. 98-103.

[35] Zhao, Z. and M.R. Iravani, Application of GTO voltage-source inverter for tapping HVDC power. Generation, Transmission and Distribution, IEE Proceedings-, 1994. 141(1): p. 19-26.

[36] Chetty, L., N.M. Ijumba, and A.C. Britten. Parallel-cascaded tapping station. in Power System Technology, 2004. PowerCon 2004. 2004 International Conference on. 2004.

[37] Nosaka, N., et al. Simulation studies on a control and protection scheme for hybrid multi-terminal HVDC systems. in Power Engineering Society 1999 Winter Meeting, IEEE. 1999.

[38] Yuan, X.F. and C. Shijie. Performance analysis of a hybrid multi-terminal HVDC system. in Electrical Machines and Systems, 2005. ICEMS 2005. Proceedings of the Eighth International Conference on. 2005.

[39] Yuan, X.F. and S.J. Cheng. Simulation Study for a Hybrid Multi-terminal HVDC System. in Transmission and Distribution Conference and Exhibition, 2005/2006 IEEE PES. 2006.

[40] Mai Huong, N., T.K. Saha, and M. Eghbal. Investigation on the impact of hybrid multi-terminal HVDC system combining LCC and VSC technologies using system identification. in Universities Power Engineering Conference (AUPEC), 2012 22nd Australasian. 2012.

[41] Billinton, R., M. Fotuhi-Firuzabad, and S.O. Faried, Reliability evaluation of hybrid multiterminal HVDC subtransmission systems. Generation, Transmission and Distribution, IEE Proceedings-, 2002. 149(5): p. 571-577.

[42] Zadkhast, S., et al., Reliability Evaluation of an HVDC Transmission System Tapped by a VSC Station. Power Delivery, IEEE Transactions on, 2010. 25(3): p. 1962-1970.

[43] Xia, C., et al. Integrating wind power plant to the grid using hybrid multi-terminal HVDC technology. in Industrial and Commercial Power Systems Technical Conference (I&CPS), 2010 IEEE. 2010.