Simulation Study of WPP-HVDC-Grid Integrated System

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Simulation Study of Wind Power Plant, VSC-HVDC and Grid Integrated System

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Abstract—**A number of large offshore wind power plants (WPP) are planned in the seas around Europe. VSC-HVDC is a suitable means of integrating such large and distant offshore WPP which need long submarine cable transmission to the onshore grid. Both VSC-HVDC and Offshore WPP are new technologies and a detailed study of their interaction, control and coordination is required. Development and simulation of an offshore WPP connected to the onshore grid by VSC-HVDC has been described in this paper.**

A sequence of operations for start-up of HVDC, energizing the offshore grid and connection of the wind turbine generators (WTG) followed by active power ramp up and ramp down has been studied. A case of fault ride through has been simulated for onshore grid faults. The model forms a means of understanding the system and its operation as a whole from power system perspective.

Index Terms—**Offshore Wind Power Plant, VSC-HVDC, grid integration, modes of operation and fault ride through (FRT)**

I. INTRODUCTION

EMPHASIS on clean and green renewable energy sources amid rising environmental concerns has led to the rapid development of wind turbine generator(WTG) technology and large wind power plants (WPP). Recently the focus has shifted to the huge potential of offshore wind energy. A total of 1471MW of offshore wind power generation, all in European seas, has been installed by the end of 2008, with 357MW of offshore WPP was installed in the year 2008 [1]. As per the reference scenario of EWEA, by 2030, the offshore WPP is expected to contribute 120 GW out of 300GW of installed wind power generation [2].

High voltage ac transmission is not suitable for long distance cable transmission [3]. VSC-HVDC provides feasible transmission link for connecting distant offshore WPP using polymer insulated submarine cables. Apart from that it has several technical advantages like fast, independent and reversible control of active flow and reactive power generation at both ends. Its controllability facilitates the WPP developers to meet the grid code requirements with regard to fault ride through, reactive power control and voltage support [4].

The WPP is assumed to be comprising of wind turbine generators (WTG) equipped with full scale converters (FSC) [5]. The full scale converter decouples the machine frequency from the offshore grid frequency thereby enabling the variable speed operation in the whole speed range of operation.

This paper describes the modeling of a WPP with VSC-HVDC connection to the onshore grid and the results of the simulation studies. Model development is described in section II. Section III describes simulation of a sequence of operational modes including a case of a low voltage fault ride through. Finally it is concluded in section V.

II. SYSTEM DIAGRAM AND MODEL DEVELOPMENT

Fig 1 shows the system being studied. A simple Thevenin's equivalent is used to represent the onshore grid, while the HVDC has been modeled in detail with switched converters and their accessories viz. controller, converter transformers, phase reactors, filters and DC capacitors, HVDC cable, DC line reactors. The assumed system data is given in the Appendix.

The WTG with their FSC's are modeled as current controlled voltage sources. When identical components are present on the offshore and onshore, suffixes '1' and '2' are used to indicate offshore and onshore components respectively.

A. Off-shore VSC and its controller

The offshore VSC controller (VSCC1) maintains the offshore grid voltage and frequency. Voltage control is achieved by applying the desired reference voltage along the d-axis while setting the q-axis voltage to 0. The rotating reference frame is selected such that the voltage phasor is aligned with the d-axis. Current references are generated from these AC voltage controllers in the outer loop. The inner loops produce the reference voltages which are augmented by the feed-forward of the voltage at the filter bus and compensation for the drop in the phase reactor [6]. Pulse width modulation (PWM) signals are generated using sine-triangle comparison as shown in Fig. 2.

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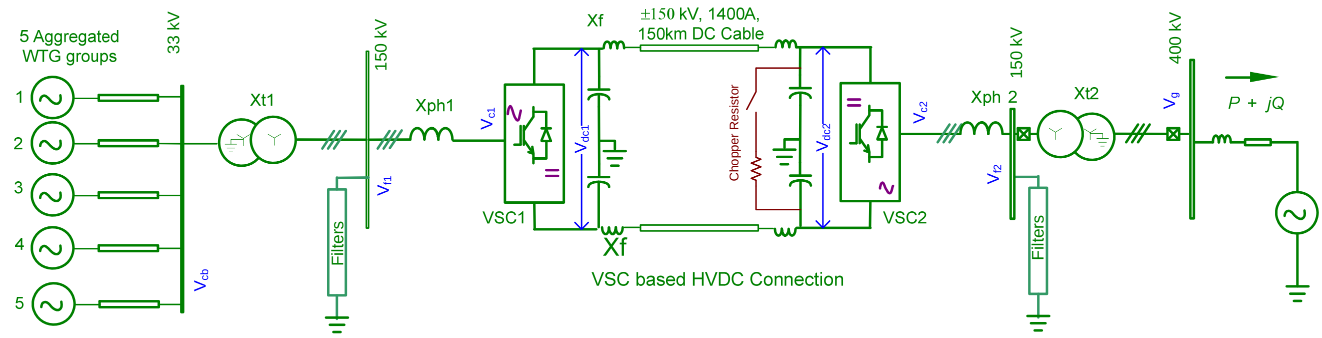

Fig. 1 WPP with VSC-HVDC connection to the grid

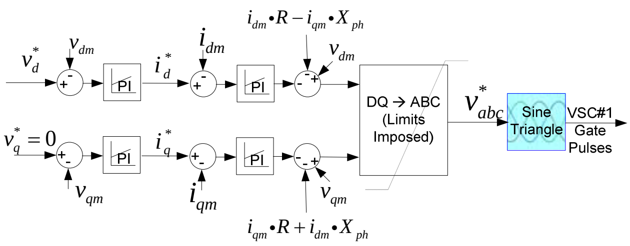

Fig. 2 Block Diagram of Offshore VSC Controller

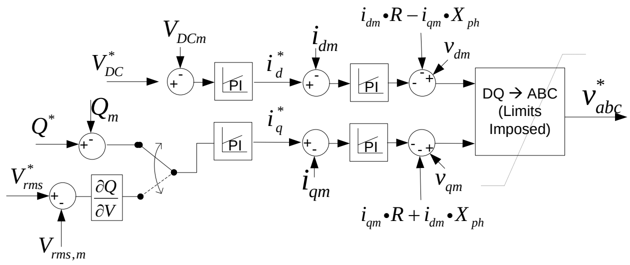

Fig. 3 Block Diagram of Onshore VSC Controller

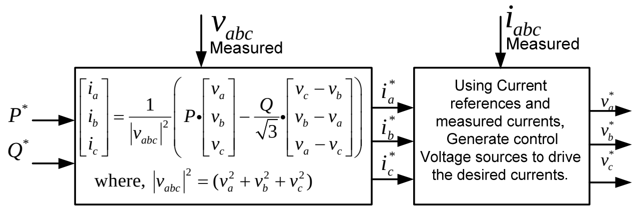

Fig. 4 Determination Voltage Source model for WTG with FSC

B. Onshore VSC Controller

The onshore VSC controller (VSCC2) regulates the HVDC voltage and the reactive power (or terminal voltage) exchanged with the onshore grid as shown in Fig 3. The HVDC voltage regulation loop sets the d-axis current reference while the reactive power is controlled by setting the q-axis current reference. These are controlled by the inner current loop controls as described in the previous section [6].

The reactive power control loop may be switched in the voltage (at PCC) control mode. Then the sensitivity of the PCC voltage with respect to the reactive power injection is used to determine the q-axis current reference.

C. WTG with FSC model

Every WTG is assumed to be equipped with its own FSC. In this simulation study the WTG with its FSC is modeled as a current controlled voltage source. As shown in Fig. 4, positive sequence component of the terminal voltage is estimated and then for a specified active and reactive power output, the phase currents to be injected into the offshore grid are computed. Second order generalized integrator (SOGI) based controllers then set the voltage source references to achieve the current injections. In this study 80x5MWe WPP is represented by 5 aggregated WTG models of 80MW each.

D. Chopper controlled resistor

Chopper controlled resistor, also referred as braking resistor in literature, is put at the dc side of VSC2 so as to dissipate the excess power and avoid the buildup of DC over-voltage when power transmission to the grid is restricted in the event of onshore grid faults [7]. The current drawn by the chopper resistors during DC over-voltage is estimated and the resistor is represented by a current sink. Hysteresis control based upon voltage measurement has been used. The chopper is turned 'ON' when the VSC-HVDC voltage exceeds 106% of the nominal. From 'ON' state it is turned 'OFF' only when the voltage falls below 101% of the nominal voltage. These threshold limits determine the over-voltage levels in the VSC-HVDC system and the switching frequency of the chopper resistor.

III. Simulation of Operation Sequence

A sequence of processes has to be followed so as to energize the VSC-HVDC link, and the offshore grid and synchronizing the WTG before power generation can be ramped up. Fig. 5 shows the power and VSC-HVDC voltage waveforms during the starting of VSC-HVDC, energizing the offshore grid and synchronization of the WTG's, power ramp up and steady-state operation at maximum generation, power ramping down to zero, disconnection of the WTG and finally shut down of the whole system.

The operation range can be divided into the following sequence of operations –

i. Charging the DC capacitors and energizing VSC-HVDC
ii. Energizing the Offshore grid
iii. Synchronization of offshore WTG and power control
iv. Steady state operation at maximum P and Q output.

A case of low voltage fault ride through using chopper controlled resistors has been included.

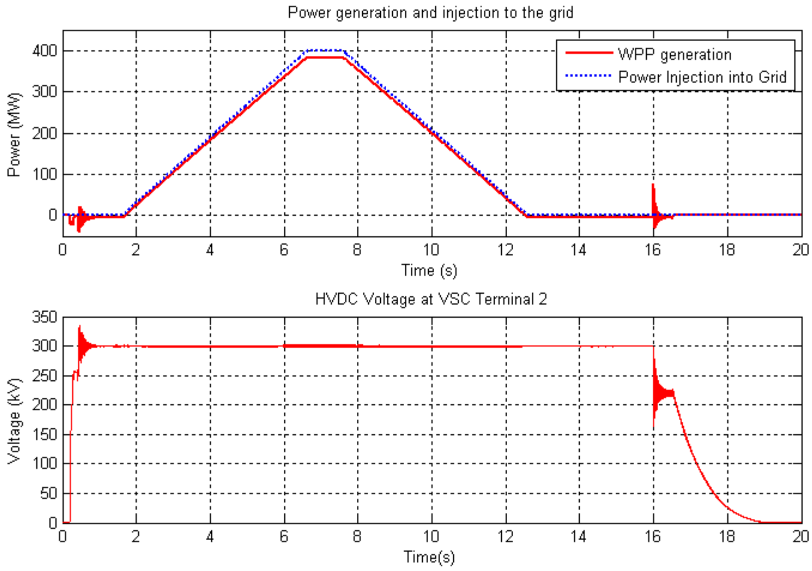

Fig. 5 Power generation and transmission and HVDC Voltage curves for a whole range of operation from start-up to shut-down.

A. Charging of VSC-HVDC

In the beginning, the VSC-HVDC as well as the offshore WPP grid is not energized. When the circuit breaker is closed to connect the converter to the grid through the converter transformer, the anti-parallel diodes in VSC2 does the rectifying action and a large inrush current flows in to charge the HVDC capacitors and the HVDC line to the DC voltage level of uncontrolled rectifiers, given by,

$$V_{dc0} = \frac{3\sqrt{3}}{\pi} V_m \qquad (1)$$

However, since the offshore VSC is blocked, the diode rectifier action of the onshore VSC sees a capacitive impedance of the cable and the DC capacitors. Hence the DC capacitors and the cables get charged to the peak line to ground voltage levels, i.e. ±122.5kV or 245kV pole-pole voltage. In Fig. 6, the voltage has risen to 255kV by the rectifier action of the diodes.

The initial magnitude of inrush current is limited by the impedance of the grid, converter transformers and the phase reactors. In this simulation, pre-insertion resistors of 1kΩ have been used for a period of 70ms.

After 200 ms, VSC2 controller is de-blocked and gate pulses are applied to the IGBT's. The HVDC capacitors and the lines then get charged to the operating voltage of the VSC-HVDC in a controlled manner. The power required for the charging and energization is drawn from the grid.

B. Energizing the Offshore grid

After the VSC-HVDC line voltage is stabilized, then the offshore VSC (VSC1) is de-blocked. Its controller ramps up the reference voltage so the offshore voltage builds up gradually. After nominal voltage level is attained in the offshore-grid, the WTG cables are connected to the collector bus one-by-one to avoid oscillations. At this point of time the WPP is fully energized, and the WTG's are ready for synchronization.

Initial charging of the VSC-HVDC and energizing of the offshore grid is shown in Fig. 6

C. Synchronization of offshore WTG and power control

The WTG's are running at rated voltage but with no load generation. The PLL in the FSC-inverter detects the magnitude and phase of the WPP grid voltage. The FSC-inverter output voltage is matched with the grid voltage at no load and then it is ready for synchronization. The breaker is closed. After that the power can be ramped up or down as per the requirement. Both active and reactive power command can be given to the FSC. While the active power comes from the WTG, VSC is capable of generating or absorbing reactive power as long as its maximum current rating is not exceeded.

D. Steady State operation

Fig 7 and 8 show the current and voltage waveforms when the WTGs are operating in steady state at no generation and at maximum power generation respectively. In Fig 7, the WPP currents are lagging the WPP voltage by approximately 90° implying that the WPP has capacitive var generation which flows towards the offshore VSC. The no load ac current waveform of the onshore VSC shows the flow of 0-sequence component.

In fig 8, the onshore VSC AC currents have a fundamental component with superimposed switching ripples. The onshore current waveform shows the current entering the onshore VSC. Hence it appears to be in phase opposition implying that the power is flowing out of the VSC towards the grid.

E. Fault Ride through Using Chopper Controlled Resistors

The grid voltage at the point of common coupling is dipped to 42kV from the 400kV nominal levels to simulate a case of low voltage fault in the onshore grid. Power evacuation to the grid is restricted and the HVDC system voltage starts building up. Sensing the over-voltage in the HVDC lines, the chopper resistor dissipates the excess energy. The impact of fault is contained in the HVDC chopper resistors.

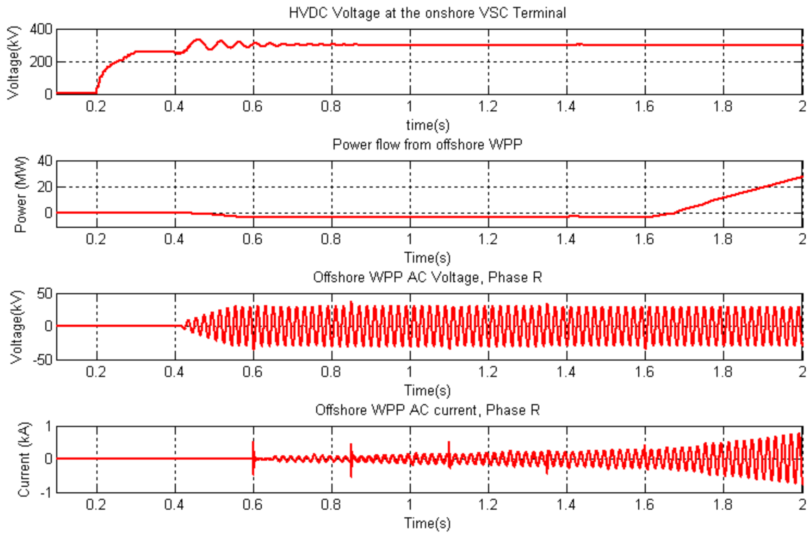

Fig. 6 Charging VSC-HVDC and energizing the offshore grid

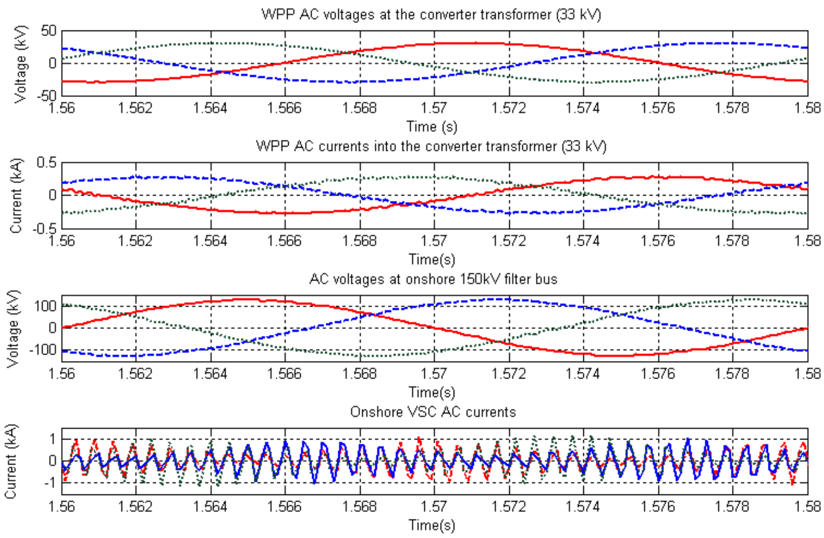

Fig. 7 Steady state operation at no load

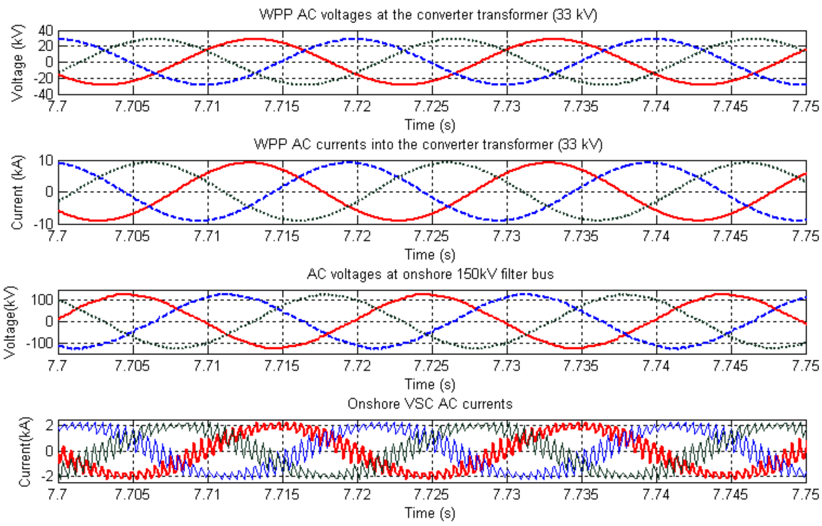

Fig. 8 Steady State operation at full 400MW WPP generation

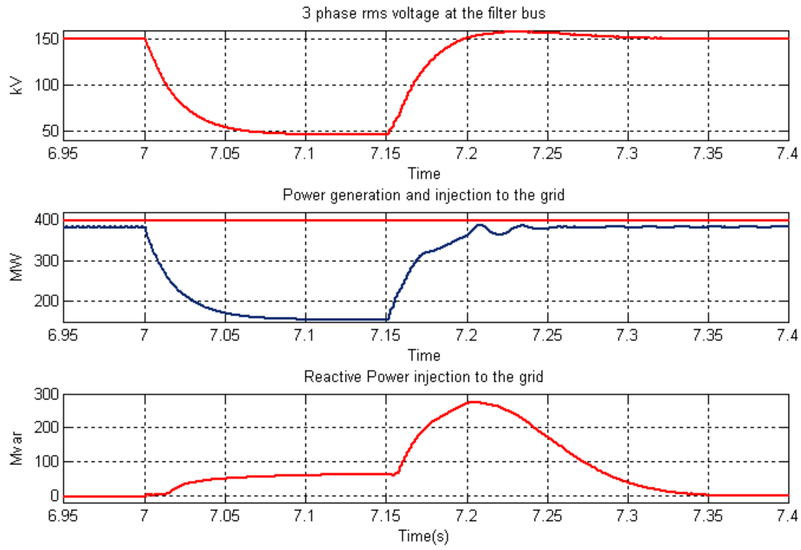

Fig. 9 Response during the low voltage fault at the PCC

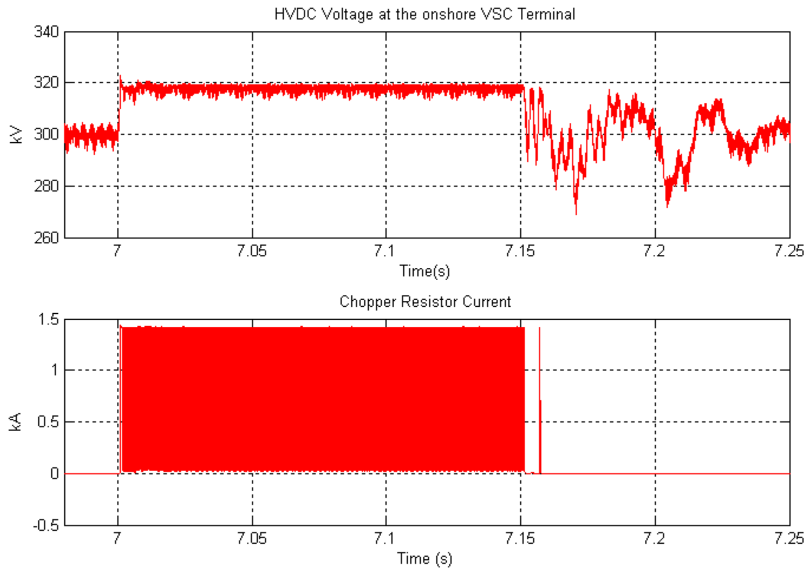

Fig. 10 Low Voltage Fault Ride through using chopper resistors.

Fig 9 shows the response of the VSC-HVDC when there is a low voltage fault at the PCC on the onshore grid. The power delivery to the grid decreases due to voltage dip. Excess energy gets accumulated in the HVDC cables and capacitors thereby increasing the HVDC voltage. The hysteresis controllers trigger the chopper resistors and dissipate the excess power. The reactive current injection is increased to the nominal current levels so as to support the grid voltage recovery. The HVDC overvoltage and the current dissipation in the chopper resistors are shown in Fig. 10.

Grid codes require that reactive current be injected into the grid during low voltage conditions, so that the voltage recovery can be supported. In Fig. 8 the reactive power injection is shown as a result of reactive current injection. Even though rated current is being injected, the reactive power appears to be low when the PCC voltage is very low. After the fault is cleared and the voltage has recovered, the reactive power injection comes down to nominal levels.

IV. Discussion

A model of WPP with VSC-HVDC connection to the onshore grid has been developed and the different operating conditions have been simulated. Operational sequence of starting up the VSC-HVDC, and energizing the offshore grid, sequential synchronization and connection of a number of aggregated WTG followed by power generation ramping up to full power level and then ramping down to 0 generation levels have been demonstrated. The simulation gives an overview of the overall system and its operation.

The low voltage fault ride through study shows that VSC-HVDC is capable of supporting the grid by injecting reactive current while dissipating the excess power in the chopper controlled resistors. The WPP does not experience the fault impact and hence the recovery after the fault is cleared is fast and stable.

The model can be elaborated for the detailed fault analysis in the wind power plants and their impact upon the WPP and VSC-HVDC integrated system.

V. APPENDIX

TABLE 1 LIST OF PARAMETERS USED IN SIMULATION

Onshore Grid			
1	Base MVA	500	MVA
2	Base voltage (rms, line-line)	400	kV
3	Short Circuit Capacity	25	pu
4	Grid Impedance Angle	80	degree
Converter Transformers (Onshore)			
1	Size	500	MVA
2	Voltage Ratio (for onshore)	400/150	kV/kV
3	Voltage Ratio (for offshore)	150/33	kV/kV
4	Leakage Reactance	0.12	pu
5	Cu-loss	0.01	pu
6	Fe-loss	0.01	pu
Phase reactors			
1	Inductance	17	mH
2	resistance	10	mΩ
HVDC System			
1	Pole to pole DC boltage	300	kV DC
2	Power rating	400	MW
HVDC Cable			
1	Cable length	200	km
2	resistance	2.797	Ω
3	Inductance	22.31	mH
4	Shunt Capacitance	28.15	uF
DC capacitors (at VSC terminal)		35.5	uF
Offshore WTG Cables			
1	Conductor Cross Section	150	sq. mm
2	Length	2	km
3	resistance	9	mΩ
4	Inductance	0.44	mH
5	Shunt Capacitance	0.295	uF

VI. REFERENCES

[1] "Seas of Change: Offshore Wind Energy," The European Wind Energy Association (EWEA), 2009.

[2] "Pure Power Wind Energy Scenarios upto 2030," The European Wind Energy Association (EWEA), Available: http://www.ewea.org/fileadmin /ewea_documents/documents/00_POLICY_document/PP.pdf

[3] T. Ackermann, *Wind Power in Power Systems; Wind Power in Power Systems*, John Wiley, 2005.

[4] S. K. Chaudhary, R. Teodorescu and P. Rodriguez, "Wind Farm Grid Integration Using VSC Based HVDC Transmission - An Overview," *Energy 2030 Conference, 2008. ENERGY 2008. IEEE*, 2008.

[5] J. Conroy and R. Watson, "Aggregate modelling of wind farms containing full-converter wind turbine generators with permanent magnet synchronous machines: transient stability studies," *Renewable Power Generation, IET*, vol. 3, pp. 39-52, 2009.

[6] Lie Xu, B. W. Williams and Liangzhong Yao, "Multi-terminal DC transmission systems for connecting large offshore wind farms," *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, pp. 1-7, 2008.

[7] A. A. Meer, R. L. Hendriks and W. L. Kling, "A survey of fast power reduction methods for VSC connected wind power plant consisting of different turbine types" presented at the 2nd EPE Wind Chapter Seminar, KTH, Stockholm, Sweden, 23-24 April, 2009.