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Improving Fault Ride ThroughCapabilities For Offshore PMSG Wind Farms Connected To VSC-HVDC Transmission System

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Abstract:-Fault ride through (FRT) is one of the most dominant grid connection requirements to be met by Wind Energy Conversion Systems (WECS). In occurrence of grid voltage dips, a mismatch is produced between the generated active power and the active power delivered to the grid. Fault ride through necessity demands management of this mismatch, which is a challenge for the WECS. Considering the development of full scale converter based wind turbine generators (WTG), use of unit rated DC controlled resistors for each of the full scale AC-DC-AC converter system of the individual turbines has been proposed instead of the one on the high voltage direct current (HVDC) line side. In this paper, both the cases have been simulated and their performances are found to be similar. Thus, it justifies that the DC resistors in the full scale converters are sufficient to handle the FRT conditions.

Keywords:-Voltage sag, DC over-voltage, Fault ride through, Wind farms, VSC-HVDC.

I. INTRODUCTION

Due to the increment in electricity demand and the increased concern for the environmental impact of the conventional fossil fuel sources, a number of new generation technology, such as wind power, solar photovoltaic, tidal power, wave power, and biomass, have been developed. Among these renewable energy sources, wind energy is high-lighted because of its fast development in the last 25 years. The total wind power installed around the world has reached 369.557 GW at the end of 2014 [1]. Only in European Union (EU) annual installations of wind power have increased over the last 14 years, from 3.2 GW in 2000 to 11.8 GW in 2014 at a compound annual growth rate of 9.8%. The majority of the wind turbines have been installed onshore, but the large-scale expansion of onshore wind is limited by factors such as the land use and visual impact [2].

Therefore, offshore wind farms (OWFs) have shown a rapid development. Moreover, the offshore mean wind speed is higher than that in onshore sites and the turbulence is much lower [3]. All these factors have made offshore wind installation rise significantly through the years.

OWFs are usually located far from load centers. Therefore, long transmission cables are required. Moreover, the capacity of these wind farms (WFs) becomes larger and larger. For such offshore network, where large power will be transmitted over long distance, application of high voltage alternating current transmission (HVAC) technology may not be feasible [4]. The reason behind is that with increasing transmission distance, the reactive power flow will be higher due to line capacitances, which will result in large line losses [5]. Thus, an alternative is to use high-voltage direct-current transmission (HVDC) technology.

Developments in the last decade in voltage source converter (VSC) technology has led to the evolution of VSC based HVDC (VSC-HVDC) transmission system. Such a VSC-HVDC transmission is capable of 4-quadrant operation enabling full control of both the active and reactive powers at both ends of the DC transmission, independently of each other.

When an OWF is connected to main grid through VSC-based HVDC, the HVDC voltage is controlled by the onshore HVDC converter which transfers the power to the onshore AC network. When a fault occurs at the AC grid, the onshore converter is unable to transmit all the active power to the AC grid, but OWF still inject active power to offshore converter, which will result in power imbalance between onshore converter and offshore converter shown in Fig.1.

The resulting power imbalance will charge the capacitance in the dc-link. Without any actions, this will result in a fast increase of the dc voltage, which may damage the HVDC equipment. Therefore some strategies should be taken to regulate the power imbalance.

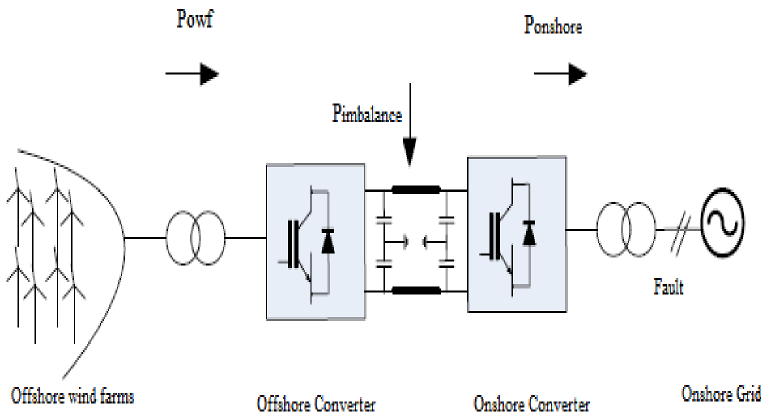


Fig.1: Fault effect on power transfer for VSC-HVDC system

This paper investigates the possible FRT methods to deal with the onshore ac fault. The model and control principle of HVDC converter and wind turbine will be first developed. Then a test system of OWF connected to main grid via HVDC will be established. After that, two FRT methods will be developed and implemented. The system will be tested under onshore short circuit conditions, to test the capability and effectiveness of the proposed FRT methods to handle these situations.

In Fig.2, synchronous generators driven by wind turbines operate at variable frequencies corresponding to their speed of operation. Two OWFs with capacity of 90MW and 90MW connected to the onshore grid via VSC-HVDC is considered as the test system. The main components are onshore grid, converter transformers, VSC, DC cable, and OWFs.

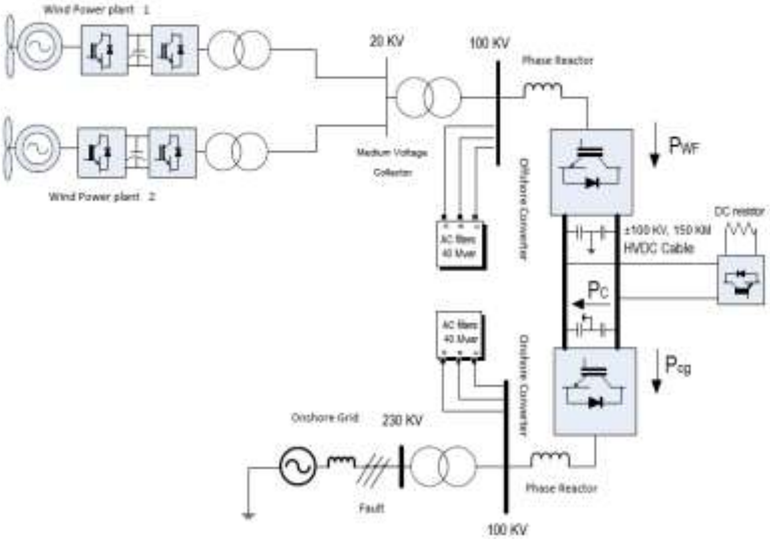


Fig.2: Test system with onshore DC resistor

Each of them is coupled to a common collector bus operating at controlled frequency of 50Hz (60Hz or other frequency of operation is equally feasible) through a full scale AC-DC-AC converter (FSC). The collector bus voltage is stepped up and then rectified to HVDC for transmission to the onshore grid. Onshore the HVDC is inverted back to HVAC and then connected to the AC grid through interconnecting transformers. Tuned filters are used at both terminals of VSC-HVDC to filter out the high frequency harmonics. Different control strategies can be adopted for the HVDC transmission system.

This paper refers to a specific case, in which the offshore VSC controls the voltage magnitude and frequency of the offshore grid voltage. Power control strategies remain with the WF-controllers. The onshore VSC regulates the DC link voltage, such that under normal operating conditions, the power injected into the DC grid is transferred to the onshore AC grid and power balance is maintained [6].

However, when there is a fault on the onshore ac grid, the AC grid voltage at the point of common coupling (PCC) dips, thereby reducing the power transfer capability from the onshore VSC-HVDC terminal. On the other hand, power generated by the WTG's cannot be ramped down instantaneously. The excess power gets accumulated in the VSC-HVDC system capacitance, thereby, leading to DC overvoltage. DC controlled resistors are used to dissipate the excess power and thus limit DC voltage rise within safe levels, while the WTG's are signaled to reduce their generation as quickly as possible. DC controlled resistors have been used in HVDC lines to prevent dc over voltages by temporarily dissipating the excess power[7]-[8].

A DC breaker consists of a DC resistor directly controlled through a power electronics switch, e.g. GTO, IGBT. It is installed in the VSC-HVDC onshore converter station as is depicted in Fig.2. The main function of DC breaker is to limit the DC voltage by dissipating the excess power as heat when a fault occurs at the AC grid. When the DC voltage exceeds its threshold value, in this paper 1.1 pu is chosen, the power electronics, e.g. GTO, IGBT, is switched on. The power is dissipated by the resistor, and thus limit DC voltage rise within safety level. When the dc voltage is below its threshold value, the power electronics, e.g. GTO, IGBT, is switched off. This method is very straightforward and the behavior of the WFs is not affected by the fault, but a WF rated dc resistor is likely very costly and it does not take the advantage of capability of the VSC-HVDC converter.

II. DC OVER-VOLTAGE AND ITS CONTROL

transfer capability from the Grid Side VSC to the grid is given by the formula,

$$P_{Cg} = \frac{V_C - V_g}{X_{ph}} \sin(\delta_c - \delta_g) \qquad (1)$$

Where,

P_{Cg} is Power transfer from the converter to the grid

$V_C \angle \delta_c$ is Converter terminal voltage (Magnitude and Phase of the fundamental component)

$V_g \angle \delta_g$ is Grid terminal voltage (Magnitude and Phase at the filter bus)

X_{ph} is Reactance of the phase reactor

The resistance, R_{ph}, of the phase reactor is negligible in comparison to the reactance and hence neglected for simplicity. From Eq. (1), if V_g drops to 0, active power cannot be transferred to the grid. The converter can, however, supply the reactive current corresponding to its current ratings. Under such circumstances, and as long as the WF power generation (P_{WF}) cannot be ramped down, the WF side VSC continues injecting the collected power into the HVDC line and the capacitors, thereby resulting in DC over-voltages. With the aid of Fig.2, DC-link dynamics can be determined by the expression as [9]:

$$P_C = P_{WF} - P_{Cg} \qquad (2)$$

Where,

P_C is the power that goes through the dc-link capacitor

P_{WF} is the power flow from WFs

P_{Cg} is the power flow to onshore grid.

The power flow through the capacitor is given by:

$$P_C = V_{dc} I_{dc} = V_{dc} C_{eq} \frac{dV_{dc}}{dt} = \frac{C_{eq}}{2} \frac{dv_{dc}^2}{dt} \qquad (3)$$

where,

V_{dc} is the DC voltage of the DC-link

I_{dc} is the DC current flowing into the capacitor

C_{eq} is the equivalent capacitance of HVDC cable and DC capacitor.

Rearranging and integrating both sides of the Eq. (3) as follows:

$$V_{dc} = \sqrt{\frac{2}{C_{eq}} \int (P_C) dt} \qquad (4)$$

Substituting P_c by using Eq. (2), the DC-link voltage can be expressed as:

$$V_{dc} = \sqrt{\frac{2}{C_{eq}} \int (P_{WF} - P_{Cg}) dt} \qquad (5)$$

If a three phase fault occurs at the onshore grid, the power transferred from the onshore converter to onshore grid P_{Cg} will be zero as the onshore grid voltage drops to zero. Based on Eq. (5), the power flow from WFs (P_{WF}) must be reduced or dissipated by DC resistor, so that the dc voltage will not increase. Based on the power flow from WFs (P_{WF}) and the DC-link voltage V_{dc}, the equivalent size of such resistor can be estimated.

Suppose, the rated power flow from WFs is P_{rated}, and the over voltage in the DC-link has to be restricted within 10% of the rated DC voltage, then the size of resistor is given by:

$$R_{DC} = \frac{(1.1 \cdot V_{dc_{rated}})^2}{P_{rated}} \qquad (6)$$

And the short time current rating of the DC resistor system has to be,

$$I_{DC\ resistor} = \frac{1.1 \cdot V_{dc_{rated}}}{R_{DC}} = \frac{1.1 \cdot P_{rated}}{V_{rated}} = 1.1 \cdot I_{rated} \qquad (7)$$

In other words, the DC resistor system has to be rated for 10% over-current, at least for the short time, and 10% overvoltage. In order to evaluate the effectiveness of DC controlled resistor method, a simulation study has been carried out on the test system during fault condition shown in Fig.2. There are different fault types, e.g. single phase to ground fault, double phase fault, and three-phase to ground fault. Three-phase to ground fault belongs to the category of symmetrical fault and it represents the most severe case, so the DC resistor is tested under three-phase to ground fault situation. The fault occurs at 10.5s and last for 200ms, and a small ground fault resistance is used.

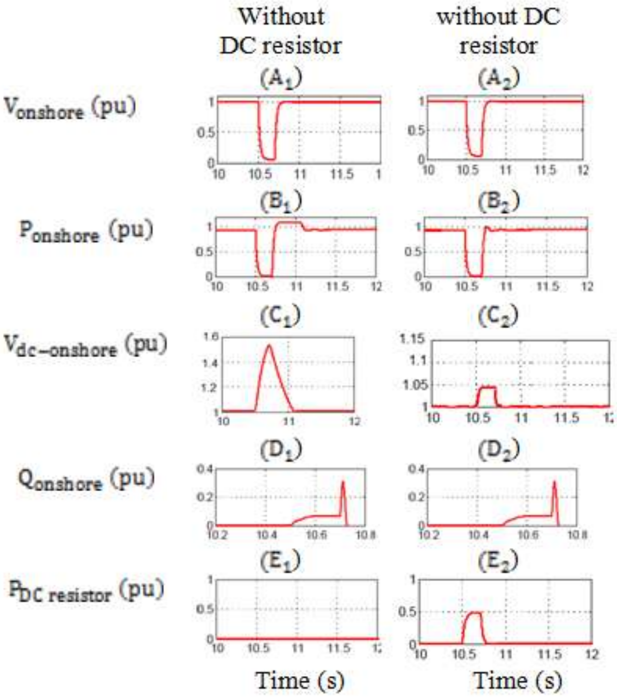
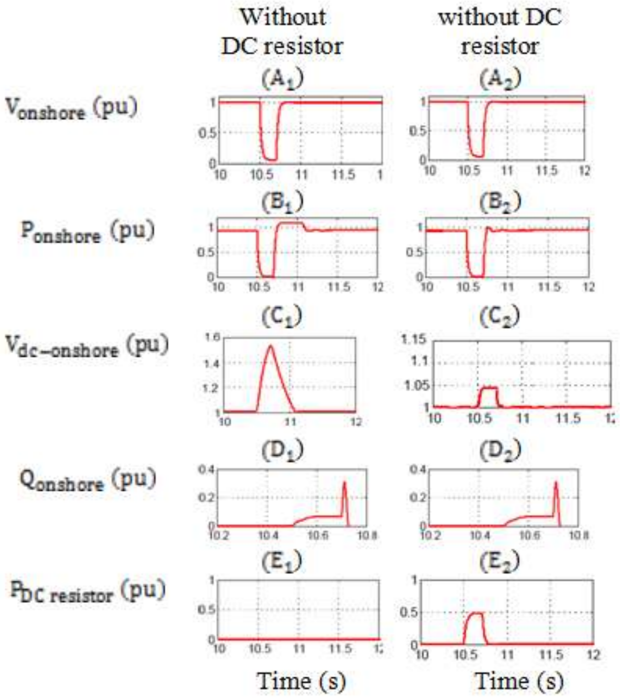
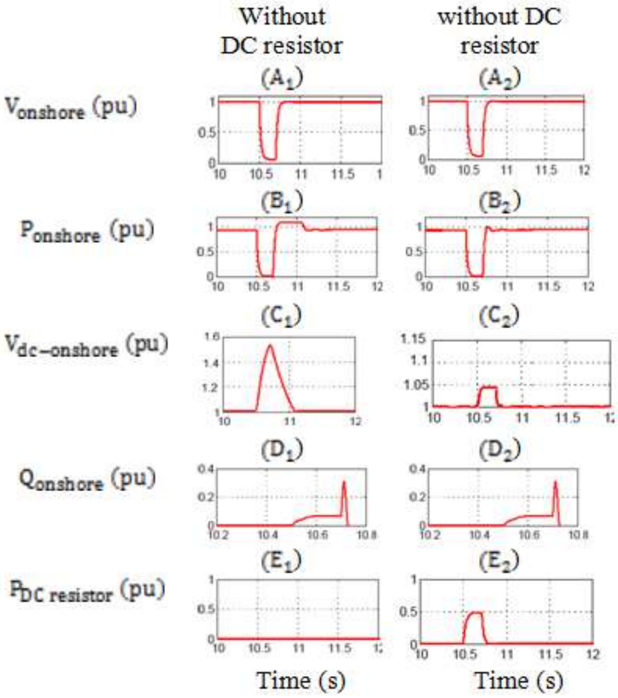
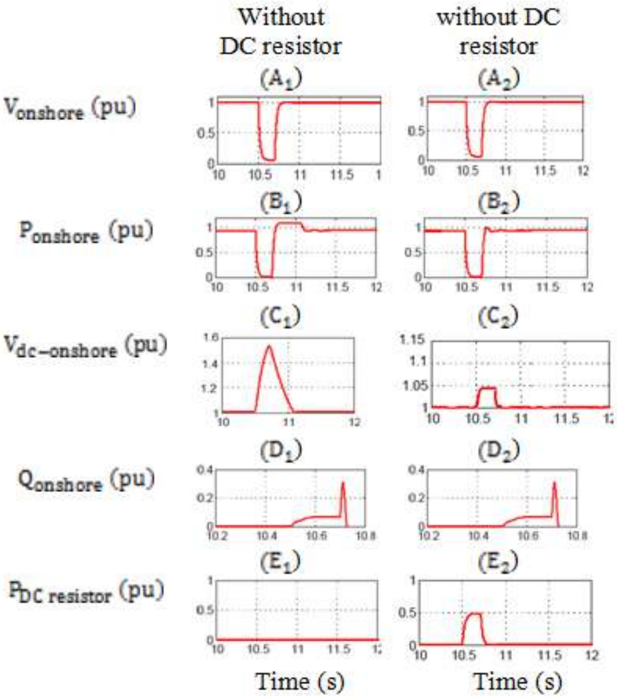


Fig.3 shows the comparison of onshore ac voltage, onshore active power, onshore DC-link voltage, onshore reactive power, resistor dissipated power without and with DC resistor. The comparison of offshore dc-link voltage, offshore ac voltage, DC voltage between wind turbine back-to-back converter, wind turbine output power without and with dc resistor is shown in Fig.4.



From Fig.3(A_1), (A_2), (B_1) and (B_2), it can be seen, after a three phase fault occurs at 10.5s, the onshore ac voltage decreases to nearly zero as is expected, which results in zero active power output. Without DC resistor, the DC-link voltage increases to 1.54 pu as shown in Fig.3 (C_1). If DC resistor is applied, the DC-link voltage is kept below 1.03 pu as shown in





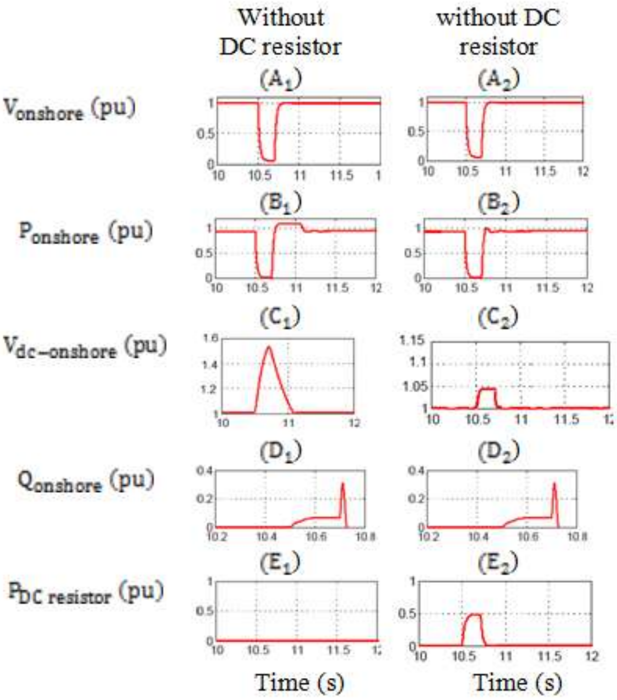


Fig.3(C_2).

Fig.3(D_1) and (D_2) show when onshore fault occurs, OWFs will produce reactive power to support grid voltage restoration. During the moment of onshore voltage recovering to normal value, there will be large reactive power drawn from OWFs.

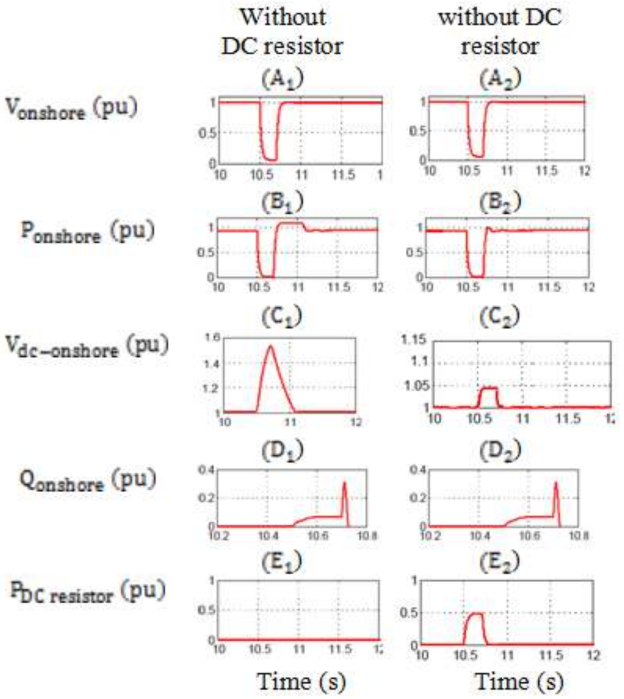
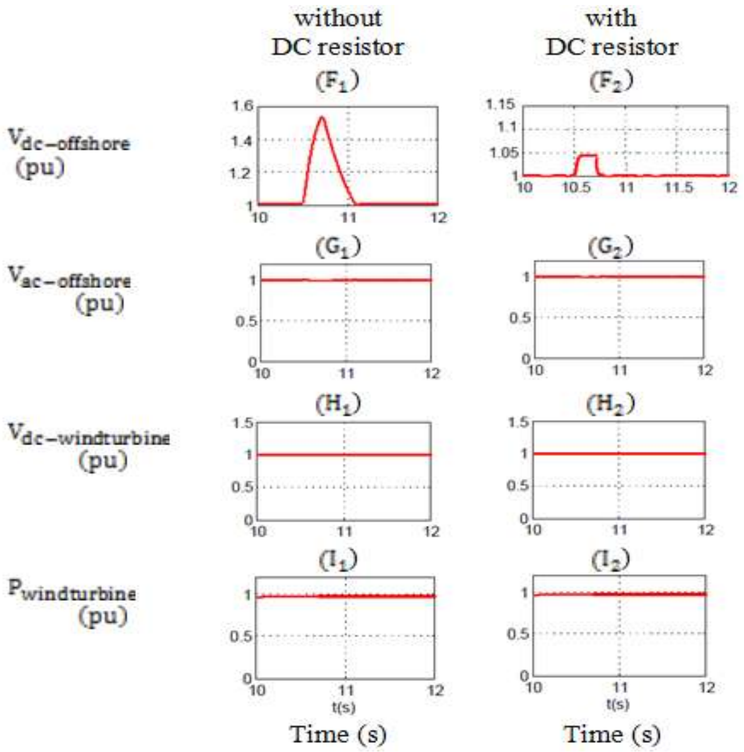


Fig.3: Onshore simulation results during three phase fault without and with DC resistor

From Fig.4(G_1), (G_2), (H_1), (H_2), (I_1), (I_2), it can be seen, the offshore ac voltage and the behavior of OWFs will not be affected by implementing DC resistor. This is a huge advantage of DC resistor for FRT.The resultant DC resistor current is shown in Fig.5. The peak current through the DC resistor is 0.425 kA.

Error! Reference source not found.summarizes the power flow, observed dc over-voltage and peak current through the dc resistor for the different voltage dips simulated.

Fig.4: Offshore simulation results during three phase fault without and with DC resistor



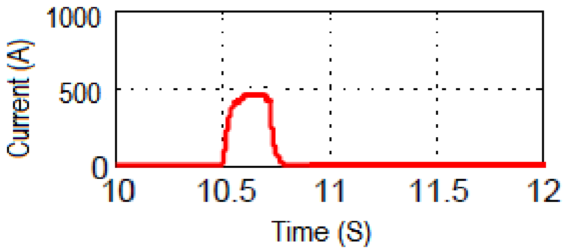


Fig.5: DC resistor current in 200 KV HVDC link during three phase fault

III. DC RESISTORS IN THE DC LINKS OF FSC-WTGS

As shown in Fig.6, DC resistors are placed on the DC- link of the WTG-FSC's. The DC resistor in the HVDC system is deactivated. When the offshore terminal DC voltage exceeds the estimated offshore DC voltage by a certain amount, say 1% (in this case), the WF side VSC generates a 'reduction factor (RF)' for the reduction in the input power. It is applied to the WTG-FSC to reduce the output power. In practice, this might be attained through a communication link or it may be signaled through a reduction of collector bus voltage and/or rise in frequency.

Fig.7 shows a block diagram for generating the reduction factor (RF). The nominal HVDC voltage at the offshore VSC terminal is estimated by adding the voltage drop in the HVDC cable resistance and inductance to the VSC-HVDC reference voltage specified at the grid side VSC and then compared with the measured offshore HVDC voltage. The over-voltage above certain threshold (LL=1%) is thus sensed and then used.

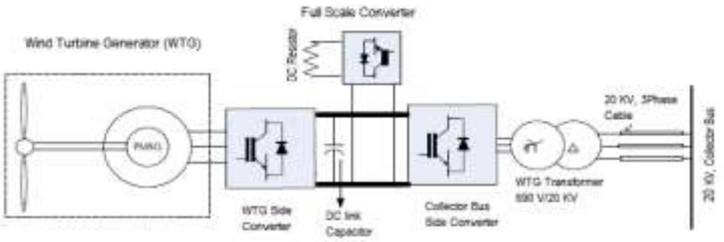


Fig.6: Wind turbine generator with full scale AC-DC-AC converter, DC resistor in the DC-link and its transformer

To determine RF, A linear function has been shown; though any other function might be used depending upon specific cases. Further the power input reduction has been assumed to fall down to 0 when the over-voltage hits or exceeds the upper threshold (HL=5%). RF may be allowed to drop down to negative values so as to facilitate the quick reduction of overvoltage.

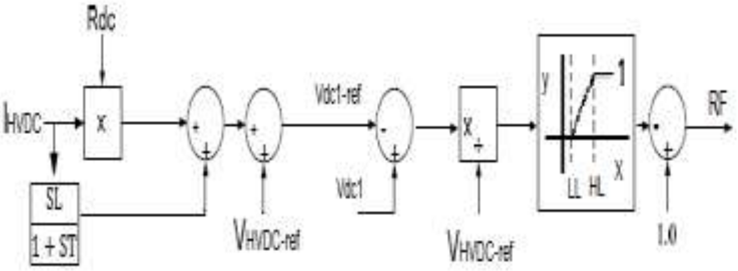


Fig.7: Generation of Reduction Factor for Active Power input to the WF-side VSC

For the simulated case when the voltage dips to 0.28 pu level at the 100kv terminal of the converter transformer, Fig.8 shows that the power input to the HVDC system is reduced progressively as the HVDC system voltage rises to 1.04 pu (observed at the grid side VSC). Fig.9 shows the DC resistor peak current rising to 282 A at the DC-link voltage of 3.4 KV.

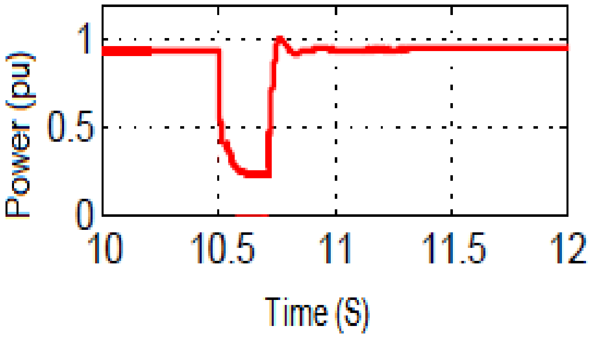


Fig.8: Power at Collector Bus and Power Transmitted to the Grid when the PCC voltage dips to 28kV

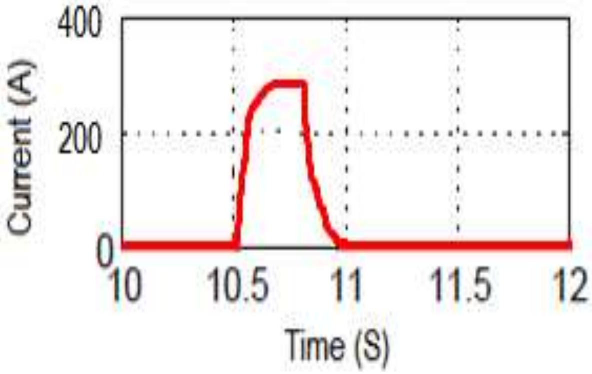


Fig.9: DC resistor current in 3.4 KV dc-Link of WTG-FSC during three phase fault

Power transferred to the grid, DC over-voltages in the HVDC lines and the full scale converters have been studied when the AC voltage at the 200kV bus of the converter transformer dips to 13kV, 28kV, 54kV and 79 kV for 200ms duration. These voltage levels are arrived at when voltage dips to 10%, 25%, 50% and 75% of nominal levels are simulated by dividing the grid impedance into two parts and connecting the fault impedance between them. DC over-voltage at the onshore terminal of VSC-HVDC, and the current dissipated in the breaker resistor HVDC for different voltage dip levels are compared with those of overvoltage in dc link of FSC in Table I.

Table I: DC overvoltage for VSC-HVDC and dc link of FSC during voltage dips of different levels at the point of common coupling.

Case A: (DC Resistors in the HVDC system is activated)
Case B: (DC Resistors in the HVDC system is deactivated)

3-phase rms voltage at PCC (pu)	Power transferred to the grid (pu)	Maximum DC overvoltage during fault (pu)			DC resistor current (KA)	
		Case A Over voltage in VSC-HVDC	Case B Over voltage in VSC-HVDC	Case B Over voltage in DC link of FSC	200 KV DC	3.4 KV DC
0.13	0.09	1.036	1.04	1.038	544	359
0.28	0.25	1.03	1.033	1.031	425	282
0.54	0.48	1.016	1.023	1.02	266	152
0.79	0.73	1.006	1.013	1.005	20	12

IV. CONCLUSIONS

Identical levels of over-voltages in HVDC system have been observed in the two models of simulated cases when the DC resistors are located in the HVDC system and when they are placed in the DC links of the full scale converters. Through this simplified simulation results, the two methods appear to perform in a similar way to check the HVDC system overvoltage.

However, using the DC resistors in the DC link of the full-scale converters has merit as the resistor size and ratings is greatly reduced when compared to a large resistor bank required when it is placed on the HVDC line. Adding the DC controlled resistors in the DC link of full scale converters will be an attractive option as these will have to face a lower DC voltage and power ratings. Further, the DC resistor on each of the full-scale converter provides them DC-link over voltage protection against faults between the full scale converter and the HVDC converter, for example a fault on the collector bus. Therefore the WTG-FSC’s should be equipped with the DC controlled resistors while the DC resistor in the HVDC may be eliminated.

REFERENCES

[1]. Global wind energy council. http://www.gwec.net/global-figures/graphs/, 2015.

[2]. J.Wilkes, J.Moccia, N.Fichaux, J.Guillet, P.Wilczek,“The European offshore wind industry–key trends and statistics 2009”, The European Wind Energy Association 5, 2010.

[3]. A. O.Rousis, & O.Anaya-Lara,“Dc voltage control for fault management in hvdc system”. Energy Procedia, vol. 80, pp. 237-244, 2015.

[4]. C. Ismunandar, “Control of multi-terminal vsc-hvdc for offshore wind power integration”, PhD Thesis. Delft University of Technology, 2010.

[5]. Haileselassie, Temesgen Mulugeta. “Control, dynamics and operation of multi-terminal VSC-HVDC transmission systems”, PhD Thesis.Norwegian University of Science and Technology. 2012.

[6]. C.Feltes, &I.Erlich, “Variable frequency operation of DFIG based wind farms connected to the grid through VSC-HVDC link”, In Power Engineering Society General Meeting, IEEE, pp. 1-7, 2007.

[7]. S. Peter,L. Stendius,“Large scale offshore wind power energy evacuation by hvdc light”, 2008.

[8]. A. A. Meer, R. L. Hendriks and W. L. Kling, “A survey of fast power reduction methods for VSC connected wind power plants consisting of different turbine types”, presented at 2nd EPE Wind Energy Chapter Seminar, KTH, Stockholm, April 2009.

[9]. O.Anaya-Lara, N.Jenkins, J.Ekanayake, P.Cartwright, M.Hughes,“Wind energy generation: modelling and control”, John Wiley & Sons. 2011.

Appendix

Table II: System Parameters used in the simulation

Onshore Grid			
1	Base Power	2000	MVA
2	Base voltage (rms, line-line)	230	kV
3	Shor Circuit Capacity	20	pu
4	Grid Impedance Angle	80	degree
Converter Transformers (Onshore)			
1	Size	200	MVA
2	Voltage Ratio (for onshore)	230/100	kV
3	Voltage Ratio (for offshore)	100/20	kV
4	Leakage Reactance	0.15	pu
5	Cu-loss	0.02	pu

6	Fe-loss	0.02	pu
Phase reactors			
1	Inductance	0.0239	H
2	resistance	0.0750	Ohm
HVDC System			
1	Pole to pole DC voltage	200	kV DC
2	Power rating	200	MW
HVDC Cable			
1	Cable length	150	km
2	resistance	2.0850	Ohm
3	Inductance	0.0239	H
4	Shunt Capacitance	34.65	µF
5	DC capacitors (at VSC terminal)	35	µF
Offshore WTG Cables			
1	Length	1	km
2	resistance	0.1153	Ohm
3	Inductance	1.05	mH
4	Shunt Capacitance	11.33	nF
5	WTG-FSC DC Voltage	3.4	kV