ANLYSIS OF A PMSG BASED OFFSHORE WIND FARM FED TO A ONSHORE GRID THROUGH HYBRID HVDC SYSTEM

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Abstract

Offshore Wind energy has huge potential to become major source of renewable energy for the modern world. For integrating wind farms to onshore AC grid Hybrid HVDC transmission systems have several advantages over conventional HVDC. This paper presents the PMSG based off shore wind farm integrating with onshore grid through Hybrid HVDC system .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, has extensive application prospects of 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).

Keywords: *Offshore wind farm, permanent-magnet synchronous generator (PMSG), high-voltage direct current link (HVDC) Commutated converter (LCC), voltage source converter (VSC).Voltage dependent current order limiter (VDCOL),Voltage dependent voltage order limiter (VDVOL).*

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1. INTRODUCTION

Wind energy is the most promising energy resource among renewable resources. Recently, the offshore wind farms are being developed and built increasingly. The main reasons for adopting the offshore wind farm are lack of the suitable onshore sites and much better wind conditions at Offshore sites The large offshore wind farms have employed the wind turbines with the PMSG In recent years [1], wind energy has become increasingly Some small-scale offshore wind farms (OWFs) are under evaluation while some large-scale OWFs have been Continuously constructing and commercially operating. When delivering large generated electric power of OWFs to power grids, inherent power punctuations have adverse impacts on the power quality of the power systems to which the OWFs[2] are connected. Actually, during the last decade of the twentieth century Worldwide wind capacity doubled approximately every three years. Currently, five countries (Germany, USA, Denmark, India and Spain) concentrate more than 83% of worldwide win energy capacity in their countries [3].

Wind farms are built on land, but in recent years there has been (and will probably be in the future) a strong trend towards locating them offshore. The lack of suitable wind turbine sites on land (it is particularly the case of densely populated countries) and the highest wind speeds located near the sea(and consequently higher energy can be extracted from the wind) are the two main reasons for locating wind farms offshore. Horns Rev in Denmark [4] is an example of a current offshore wind farm, which is capable of producing 160 MW.

Mainly, three types of induction generators are used in wind power conversion systems: cage rotor, wound rotor with slip control and doubly fed induction motors. The last one is the most utilized in wind speed generation because it provides a wide range of speed variation. However, the variable-speed directly-driven multi-pole permanent magnet synchronous generator (PMSG) wind architecture is chosen for this purpose and it is going to been modeled: it offers better performance due to higher efficiency and less maintenance because it does not have rotor current. What is more, PMSG can be used without a gearbox, which implies a reduction of the weight of the nacelle and reduction

The traditional line-commutated-converter (LCC) based HVDC (LCC-HVDC) achieves rapid development for its large transmission capacity, fast control of active power and low capital cost. However, it could not play its role when serious fault occurs in the receiving AC grid [5]. With the development of power electronic devices and control technology, the voltage source converter (VSC) based HVDC (VSC-HVDC) has been developed rapidly since the 1990s. VSC-HVDC can control the active and reactive power in- dependently and transmit power to the weak AC system or the passive network. However, VSC has a limited range of power capacity and cannot defense against DC fault. In addition, its switching loss and capital cost are higher than those of LCC-HVDC. Nowadays, VSC has greater ad- vantages in the weak AC system transmission and renewable energy generation integration to the main grid [6].

The hybrid-HVDC topology, which consists of LCC and VSC, combines their advantages [7]. LCC-HVDC has large transmission capacity and high voltage rating. Hybrid-HVDC, adopting LCC on rectifier side and VSC on inverter side, has the advantages that it can improve the operating characteristics of the AC system on the receiving side. Compared with VSC-HVDC, it has lower switching loss and smaller investment. Most research on hybrid-HVDC of this structure is about the steady-state operation, connection to a weak AC system or the passive network and fault characteristics [8–13]. This paper focuses on the hybrid-HVDC, adopting VSC on rectifier side and LCC on inverter side. Although the commutation failure may occur on inverter side, the probability of the commutation failure can be decreased through the study of the control method. Nowadays, renewable energy power generation especially the wind power develops rapidly. This kind of hybrid-HVDC takes the advantage of VSC that it requires no external commutation support and can control the AC bus voltage flexibly compared with LCC. Mean- while, it combines the advantages of LCC and VSC, reduces the loss and investment. Therefore, this kind of hybrid-HVDC has unique advantage and competitiveness in remote offshore wind farms connecting to the grid.

Many scholars have conducted valuable research on this kind of hybrid-HVDC. In ref. [14], the reasonable control strategy is designed for hybrid-HVDC and the simulation about the change of the wind speed and the faults condition is made to verify the effectiveness of the control strategy. In ref. [15], it used the direct power control without the inner loop to control the active and reactive power of VSC, which has fast dynamic response and can deal with the uncertain parameters of the outer loop. The voltage dependent current order limiter (VDCOL) is added in the constant DC current control at the LCC inverter while rectifier VSC adopts the constant DC voltage control in ref. [16], it also studies the system performances under steady-state and DC side short circuit fault condition.

This paper presents in order improve the reliability of power supply ,the paper uses bipolar hybrid-HVDC adopts VSC and inverter adopts LCC. The mathematical model of hybrid-HVDC is deduced to analyze the characteristics of the system. A novel coordinated control method is designed. A voltage dependent voltage order limiter (VDVOL) is designed based on the constant DC voltage control on the rectifier VSC side, and constant extinction angle backup control is introduced based on the constant DC current control with VDCOL on the inverter LCC side. The simulation results in PSCAD/EMTDC verify that the proposed coordinated control method which enables good steady-state performances can reduce the probability of commutation failure and improve the fault recovery performance of the hybrid-HVDC system.

This paper is organized as follows. System configuration and employed models for the studied permanent-magnet synchronous generator (PMSG) based OWF fed to onshore grid through hybrid -HVDC system.

2. CONFIGURATION OF THE STUDIED SYSTEM.

PMSG-based OWF fed to a Onshore grid system through an hybrid-HVDC system of 100 km. The 300-MVA OWF represented by a large equivalent aggregated wind PMSG driven by an equivalent aggregated variable-speed wind turbine (VSWT) is connected to the rectifier station of the hybrid-HVDC link. The inverter station of the hybrid-HVDC link is connected to ac system. The employed mathematical models of the studied system are described as below. The equations in the following subsections are expressed in per unit (pu) except that the time variable and base angular frequency are in seconds (s) and radians per second (rad/s), respectively.

2.1Wind Turbine Model

The captured mechanical power (in W) of a VSWT is

$$P_m = 0.5\, \boldsymbol{\rho}\, A_r . V_w^3\, C_p(\lambda,\beta)$$

Where $\boldsymbol{\rho}$ is air density(kg/m^3), A_r blade impact area(m^2) V_w wind speed (m/s), C_p is the dimensionless power coefficient. The power coefficient is given by

$$C_P(\lambda_i, \beta) = C_1 (C_2\lambda_i - C_3.\beta - C_4.\beta^{C5} - C_6) \exp(-C_7\lambda_i)$$

$$\lambda = \frac{RbwWbw}{Vw}$$

Wbw is the blade angular speed (rad/s), Rbw is the blade radius(m), λ is the tip speed ratio $\beta$is the blade pitch angle (degrees) C_1- C_9 are the constant coefficients of C_P . The cut-in, rated, and cut-out wind speeds of the 12,and 25 m/s, respectively. When, is set to be 0; when, the pitch-angle control system activates and β increases

2.2 PMSG Model

The mathematical model of the PMSG for power system and converter system analysis is usually based on the following assumptions [17], [18]: the stator windings are positioned sinusoidal along the air-gap as far as the mutual effect with the rotor is concerned; the stator slots cause no appreciable variations of the rotor inductances with rotor position

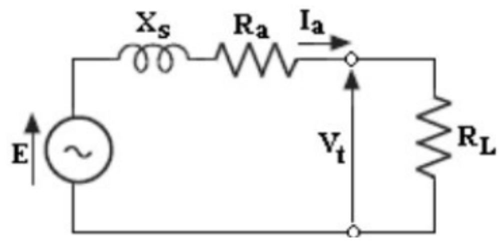

Fig-1 Equivalent circuit PMSG for one phase

The rotor reference frames of the voltages

$$U_{sd} = R_s i_{sd} + L_{sd} - \omega_s L_{sq} i_{sq} \omega_e$$

$U_{sq}=R_s i_{sq}+U_{sd} -\omega_s L_{sd} i_{sd}\omega_e$

where subscripts sd and sq refer to the physical quantities that have been transformed into the d-q synchronous rotating reference frame $U_{sd,}U_{sq}$Stator voltages in d-q axis $i_{sd,,}$ i_{sq} Current in the in d-q axis,Rs Stator resistance $L_{sd,}$ L_{sq} inductance in d-q axis.

3. STRUCTURE OF HYBRID-HVDC

The hybrid HVDC configuration is shown in Figure 1. The VSC side is composed of transformer, commutation reactor, DC capacitors, two 2-level VSC in series in order to raise the transmission capacity and voltage rating, etc. The inverter side uses the bipolar 12-pulsation LCC converter, transformer, filter, smoothing reactor, etc. The structure allows voltage rating and capacity of VSC to match with that of LCC, and improves the reliability of power supply with its unipolar operation state under DC line pole to ground fault condition.

3.1 Principle of Hybrid HVDC

For the VSC side, it can control the active and reactive powers independently by controlling the phase angle and the fundamental amplitude U_{C1} of the VSC output voltage (modulation *M*) as follows [16]:

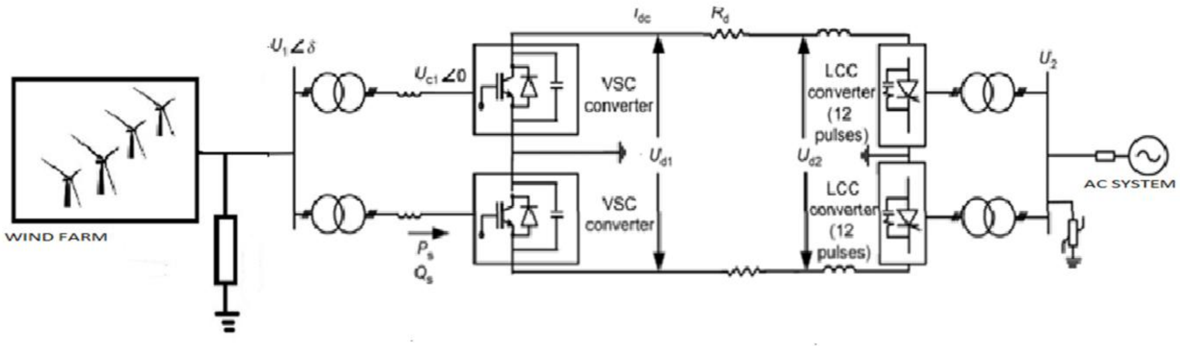

Fig-2 Configuration diagram of PMSG based Off shore Wind Farm fed to AC system through Hybrid- HVDC system

$$\text{Ps} = \frac{U1Uc1}{X} sin\delta$$

$$\text{Qs} = \frac{U1(Uc1cos\delta - U1)}{X}$$

Where X is the equivalent reactance of the converter transformer and reactors

The DC voltage of the rectifier VSC is shown when SPWM modulation is used

$$Ud1 = 2\sqrt{2Uc1}/\sqrt{3M}$$

For the inverter LCC, the only controllable value is the firing angle α(or the advanced trigger angle β=π-α). The DC voltage of the inverter LCC is

$$\text{Ud2} = 1.35U2cos\beta + \frac{3}{\pi}\text{XrIdc}$$

Where Xr is the equivalent commutation reactance.

The commutation angle μ at the inverter is shown

$$\mu = \arccos\left(cos\gamma - \frac{2XrIdc}{\sqrt{2}U2}\right) - \gamma$$

The DC current is shown

$$\text{Idc} = \frac{Ud1 - Ud2}{Rd}$$

Where Rd is the resistance of the DC line

It can be got from eqs. (2)–(4) that the DC voltage of the inverter will drop when the inverter side AC bus voltage drops. Then, the DC current will increase, the commutation angle μ will increase, thus the extinction angle γ will decrease too. As a result, the commutation failure may occur.

$$\mu = \arccos\left(cos\gamma - (2Xr\frac{U_{d1} - U_{d2}}{Rd}\right)/(\sqrt{2}\text{U}_2)) - \gamma$$

From eq. it can be seen that the DC voltage of the rectifier Ud1will affect the commutation angle μ. The μwill decrease with the decrease of Ud1, then give some margin for γ. Therefore, the rectifier VSC and inverter LCC are mutually coupled through the DC side. The DC voltage of the rectifier side will have an impact on the commutation failure, which can be a guideline for the following control.

4 THE COORDINATED CONTROL METHOD OF HYBRID-HVDC

4.1 Basic Control Method of Hybrid-HVDC

In this paper, VSC adopts constant AC voltage control [19] since hybrid-HVDC studied here is used to connect wind farms. Because the DC side of VSC is equivalent to a DC voltage source, it adopts constant DC voltage control. The DC side of LCC is equivalent to a DC current source, so it adopts constant DC current control with additional VDCOL. The main task of VDCOL is to limit the DC current when DC voltage or AC voltage decreases to a specified value [20]. It can reduce the probability of commutation failure, help the system recover rapidly after the fault and avoid the valve stress caused by the continuous commutation failure.

4.2 The Coordinated Control Method of Hybrid-HVDC

To improve the immunity of commutation failure for the LCC converter in hybrid-HVDC, this paper proposes a new coordinated control method to suppress the commutation failure based on the mathematical model of hybrid-HVDC.

4.2.1Constant Extinction Angle Control in LCC

The controller for inverter LCC is shown in Fig2.According to the characteristics of constant DC current control in LCC, when the DC current increases, the β1 of inverter will decrease and so is the extinction angle γ, which may cause the commutation failure. Thus, the constant extinction angle control is presented as the backup for constant DC current control. After the fault, γ, will decrease, so the constant extinction angle controller will increase β2 and give more margins for γ. The maximum β is chosen from β1 and β2 to trigger the converter. It should be noted that, β2should be smaller than β1to make the converter operate in the constant DC current mode. The difference between β1 and β2should not be too small which may cause the frequent switching between the two control modes, meanwhile, it should not be too large, which may cause β to drop too much when control mode switches. The designed control method can give more margins for γ by suppressing he reduction of β, which could reduce the probability of commutation failure.

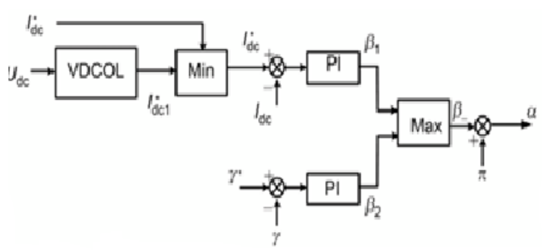

Fig-3 Configuration diagram of the LCC controller with constant

4.2.4 VDVOL Control in VSC

The principle of VDVOL. The proposed controller for VSC is shown in Figure 3. VDVOL is added to the constant DC voltage control in VSC. The principle of VDVOL is to decrease the reference value of the DC voltage when the fault at LCC's AC bus bar is detected. The DC voltage reference value depends on how much the AC bus bar voltage on LCC side drops. The DC voltage and power supply will recover to normal condition after the fault is cleared. According to eq. (6), the proposed method can reduce the probability of commutation failure by decreasing Ud1and suppressing the rise of the DC current when the fault is not serious, it also can improve the fault recovery performance when the fault is serious and commutation failure is inevitable.

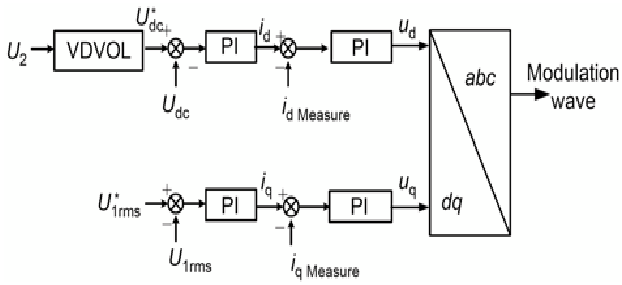

Fig-4 Configuration diagram of the VSC controller with VDVOL.

The parameter design of VDVOL Derived from eqs

$$U_{d1} = 1.35cos\alpha U_2 + I_{dc}(R_d - \frac{3}{\pi}Xr)$$

The reference value of the DC voltage Ud1of rectifier VSC has a linear relation with inverter AC side bus voltage U2. To prevent commutation failure, the parameter of VDVOL Finally, the characteristic curve of Ud–Idof hybrid-HVDC is shown in Figure 4.

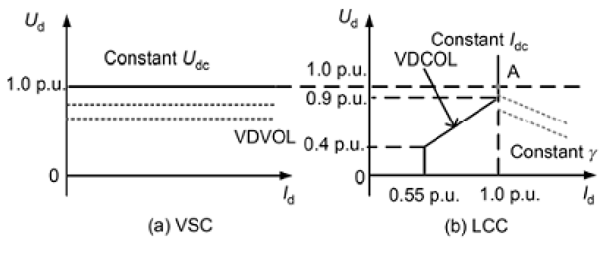

Fig-5 The characteristic curve of Ud–Id of hybrid-HVDC (A is the steady-state operating point).

5. SIMULATION RESULTS

PMSG based offshore wind farm power supplied to the onshore grid through hybrid –HVDC system.

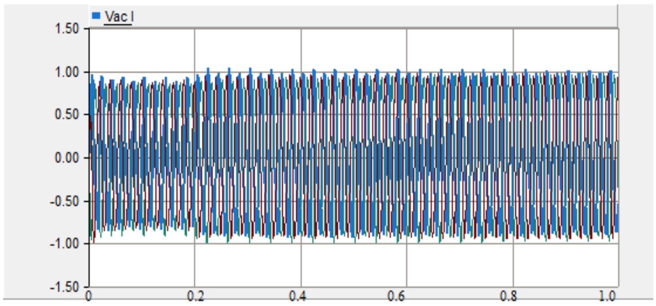

Fig-6 Steady state wave form of AC system voltage

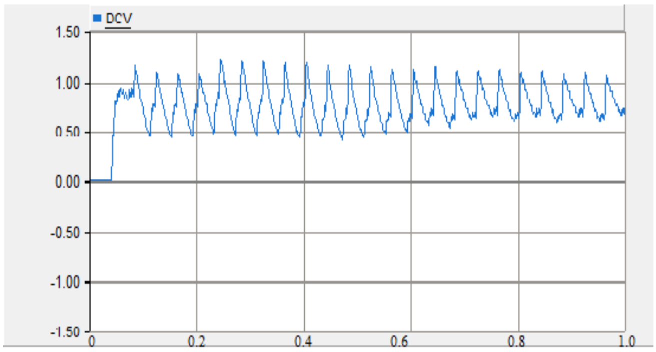

Fig-7 Study state waveform of Hybrid-HVDC link voltage

In Fig-6 Inverter AC side steady state voltage waveform has been shown. In Fig-7 Hybrid HVDC link voltage has been shown in steady state.

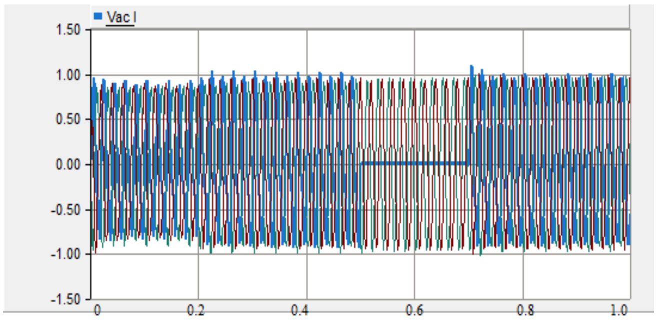

Fig-8 wave form of AC system voltage for LG fault

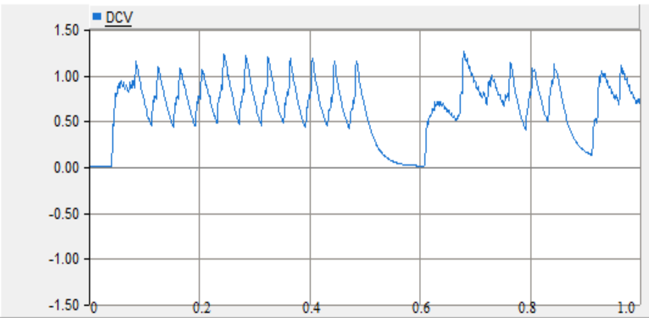

Fig-9 wave form of Hybrid-HVDC system voltage for LG fault

In Fig-8 and Fig-9 fault is simulated at 0.5 second and fault duration is 0.5-0.7 seconds for LG-fault. After applying fault voltage has been dipped from1.00 P.U to 0 P.U and after 0.7 seconds voltage waveform has been stabilized

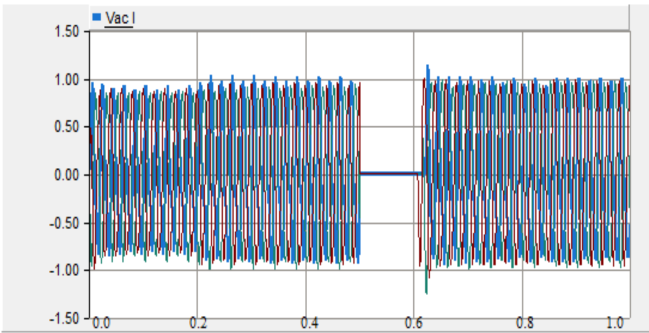

Fig-10 wave form of AC system voltage for LLLG fault

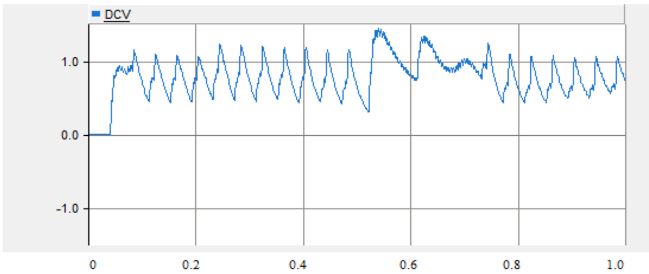

Fig-11 wave form of Hybrid-HVDC system voltage for LLLG fault

In Fig-8 and Fig-9 fault is simulated at 0.5 second and fault duration is 0.5-0.7 seconds for LG-fault. After applying fault voltage has been dipped from1.00 P.U to 0 P.U and after 0.7 seconds voltage waveform has been stabilized

Rated power	3MVA
Rated frequency	50
No pole pairs	100
Rated voltage	0.69KV
Rated current	1450A
Xd	0.4pu

Table -1 PMSG machine parameters

5. CONCLUSIONS

The modeling of a PMSG (permanent magnet synchronous generator) based offshore wind farm fed to a onshore AC grid through hybrid-HVDC system designed and simulated to the PSCAD/EMTDC.In fault accrued in inverter ac bus bar the dc link voltage will be very less effect.

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