Frequency regulation participation of offshore wind farm integrated by diode-rectifier HVDC system

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Abstract: Large-scale wind farms integrated with multi-terminal direct current (MTDC) system decouples the frequency between the wind farms and the receiving end, resulting in weakened frequency regulation ability of the onshore AC grid. Recently a new topology is proposed, called diode rectifier based HVDC, which recouples the wind farm and onshore AC system due to its characteristics, where offshore AC voltage changes with the DC voltage of HVDC system. A coordinated power control strategy for frequency regulation participation is proposed in this paper for offshore wind farms connected with diode-rectifier based high voltage direct current (HVDC) system. Considering the primary frequency and inertia response control, variable power supplementary control is implemented in wind turbines, and a telecommunication-less method of frequency event detection via the receiving offshore AC voltage is proposed, avoiding communication delay and communication failure. Simulations using EMTDC/PSCAD show that frequency dip can be accurately detected by the AC voltage of offshore wind farm, and wind farm can quickly compensate active power.

1 Introduction

To alleviate the problem of energy crisis and worsening ecological environment, offshore wind farms are getting more and more attention. Technologies for integrating large scale offshore wind farms over long distance and the design of wind farm internal collection grid become increasingly significant. HVDC transmission technology has been regarded as the main solution for integration of offshore wind farms [1]. However, there still exist problems about LCC-HVDC and VSC-HVDC, such as the characteristics, where offshore AC voltage changes with the DC voltage of HVDC system. A coordinated power control strategy for frequency regulation participation is proposed in this paper for offshore wind farms connected with diode-rectifier based high voltage direct current (HVDC) system. Considering the primary frequency and inertia response control, variable power supplementary control is implemented in wind turbines, and a telecommunication-less method of frequency event detection via the receiving offshore AC voltage is proposed, avoiding communication delay and communication failure. Simulations using EMTDC/PSCAD show that frequency dip can be accurately detected by the AC voltage of offshore wind farm, and wind farm can quickly compensate active power.

2 Topology of DR as internal collection grid

The offshore wind farm collected by DR is shown in Fig. 1, which consists of three WT clusters. Each cluster is made up of three WT strings with five fully rated converter based WTs. The offshore ac grid is connected to offshore DC grid using a 12-pulse diode rectifier, which consist of two 6-pulse diode bridges, making better power quality at the collection point of AC grid. Also, reactive power compensation and harmonic filtering is carried out by the capacitor and filter banks. The onshore VSC controls the DC voltage of the DR-HVDC link.

Each cluster can be connected to the DC link in series or in parallel. But in this paper only parallel connection is studied since the parallel topology is easier for insulation to implement and more flexible way of expansion [16]. Also, this topology can be used in the DC wind system in the future.

3 Model and control strategy of wind farm

3.1 Wind turbine model and machine side converter control

The mechanical power captured by the wind turbine from the wind can be described as [17]:

$$P_m = 0.5 \rho Av^3 C_p(\lambda, \beta)$$  \hspace{1cm} (1)

Where \( \rho \) is the air density (Kg/m\(^3\)). \( A \) is the swept area (m\(^2\)); \( C_p \) is the power coefficient of the turbine, which is a function of tip speed ratio (\( \lambda \)) and pitch angle (\( \beta \)), and \( v \) is the wind current speed (m/s).
The power coefficient and the tip speed ratio can be given as:

\[
\begin{align*}
C_p(\lambda, \beta) &= 0.22 \left( \frac{116}{\lambda_1} - 0.4\beta - 5 \right) e^{-12.5/\lambda_1} \\
1 &= \frac{1}{\lambda + 0.008\beta} \quad 0.035 \\
\lambda &= \frac{a_{\omega N} R}{\omega}
\end{align*}
\]

(2)

where \(a_{\omega N}\) is the speed of wind turbine (rad/sec), \(R\) is the radius of the turbine blades (m).

As mentioned before, the grid-side converter needs to control AC voltage of the collection point, so the machine-side converter bears the responsibility of DC voltage control. The control block diagram of machine side converter can be obtained as shown in Fig. 2. The no further discussion of detailed controls for the DC voltage is given here.

### 3.2 Grid-side converter

When integrated by diode rectifier, the grid-side converters have to establish the frequency and voltage of the offshore network [5, 6]. The mathematical model of AC voltage at collection point of offshore wind farm in the dq reference frame is shown as the equations below:

\[
\begin{align*}
L_{eq} \frac{d}{dt} I_d &= -R_{eq} I_d + a_p I_q + U_{N_d} - U_{dc} \\
L_{eq} \frac{d}{dt} I_q &= -R_{eq} I_q - a_p I_d + U_{N_q} - U_{eq} \\
C_F \frac{d}{dt} U_{dc} &= I_d - I_{Rad} + a_p V_{eq} \\
C_F \frac{d}{dt} U_{eq} &= I_q - I_{Rad} + a_p V_{eq}
\end{align*}
\]

(4)

where \(C_F\) is the filter capacitor, \(R_{eq}\) and \(L_{eq}\) are the respective equivalent resistance and inductance; \(U_{eq}\) is the voltage of the collection point.

When diode-based rectifier is conducting, the relationship between AC and DC voltages on both sides of the rectifier is shown:

\[
\begin{align*}
U_{dc} &- hvdc = M \left( 1.35 N U_F - \frac{3}{\pi} a_p L_F I_{dc} - hvdc \right) \\
P_F &= U_{dc} - hvdc I_{dc} - hvdc
\end{align*}
\]

(5)

where \(M\) is the number of 6-pulse diode bridge in series, \(N\) is the rectifier transformer turns ratio, and \(L_F\) is the rectifier transformer leakage inductance. According to the equation, the DC voltage of HVDC link can be set by power of wind farm.

As WT cluster usually consists of multiple wind power systems, there should be coordinate control strategy between the WTs. Here droop control is selected, where multiple wind power generation systems jointly control the AC voltage of the offshore wind farm. According to the dynamics analysis of network and the characteristic of diode based rectifier, a \(P/V\) and \(Q/f\) control strategy is proposed [6], to determine the active and reactive power delivered by the inverter.

Based on the equation above, the control strategy of single grid-side converter is shown in Fig. 2, which includes current inner loop, AC voltage outer loop and droop loop. In Fig. 2, LC filter is used, and wind power system is integrated into grid via transformer. The droop loop is described by:

\[
\begin{align*}
U_F &= U_{FN} + K_p (P' - P) \\
a_p &= a_{\omega N} - K_q (Q' - Q)
\end{align*}
\]

where \(U_F\), \(a_p\) are reference value of AC offshore voltage, \(U_{FN}\), \(a_{\omega N}\) are rated value, \(K_p\), \(K_q\) are droop coefficient, \(P'\), \(Q'\) are reference value and \(P'\) usually is the MPPT value and \(Q' = 0\).

As we know, the droop control can omit communication compared with the central control, but the signal bus is essential since there is still upper layer controller to send dispatch orders to those single WT. So a new control strategy is proposed, which combines the droop control and the CAN signal. The control diagram is shown in Fig. 3.

As there may exist delay, this strategy is only used for the start-up procedure. Once the start-up is finished, the reactive droop control will activate to ensure reactive power sharing in the system, as shown in Fig. 4. If big disturbance occurs at the wind farm, the angle from the integration controller will work again.

### 3.3 Droop parameter analysis

The concept of dynamic or time-varying phasors has been developed for a balanced, three-phase power system, enabling to analyse the small-signal stability of droop control for inverters connected to a distribution grid Figs. 5 and 6.
The dynamic model of the grid-side converter is:

\[ G_P(s) = \frac{3(sL + R)E_1}{(sL + R)^2 + (oL)^2} \]

\[ G_Q(s) = \frac{3(sL + R)E_1}{(sL + R)^2 + (oL)^2} \]

and \( K_P \), \( K_Q \) are the droop gain respectively. \( G_{LP}(s) \) is the transfer function of low pass filter.

With the open loop transfer function of:

\[ P_G(s)H(s) = K_P G_P(s) G_{LP}(s) \]

\[ Q_G(s)H(s) = K_Q s G_P(s) G_{LP}(s) \]

The root locus can be obtained as shown in Fig. 7 and the droop gains can then be selected.

3.4 Control of onshore VSC

The onshore VSC controls the DC voltage of the HVDC link and no further discussion is given here.

4 Primary frequency control of system

4.1 Wind pitch control and frequency support strategy

Conventional power plants usually restrict their power generation to maintain spinning power reserve to be used to counteract power fluctuations during disturbances in the system. This principle can also be applied to renewable generators.

\[ \frac{\Delta P_W}{P_{WN}} = \frac{\Delta f}{f \sigma} \]  

where \( \sigma \) is the difference coefficients of generators and \( \sigma = 10\% \) is used in this paper, \( P_{WN} \) is the rated power of wind farm, \( \Delta P_W \) is the power participating frequency adjustment. To provide additional active power, the wind farm clusters are operated to contain 5% active power reserve, considering a 0.2 \( \text{Hz} \) deviation to meet the system frequency regulation capacity requirement.

There are two ways to participate frequency regulation. One is the rotor speed control, which can cause voltage dip [7]. The second one is to control the pitch angel, which is used in this paper. From (1)–(3), Fig. 8 is drawn. It can be known that the output power is linear with the pitch angel when the wind turbine tracks the suboptimal curves since \( C_P \) and \( \lambda \) remains a constant.

So the control diagram is shown in Fig. 9. From (5), it can be known that the AC voltage will decrease if the DC link voltage of the HVDC decreases with the shortage of active power at onshore ac system. Once the fluctuation of the AC voltage exceeds the threshold voltage, pitch angel will be changed to release the active power reserve. Before the pitch angel reaches its value, temporary active power will be produced by overcurrent capability of converter of wind farms. The number of wind turbines participating frequency support can be designed based on the requirement of system.

4.2 Frequency support control of VSC

The frequency support method is to increase/ decrease the value of \( U_{\text{dcref}} \) depending on whether the converter detects a frequency dip at its AC connection point. The control block strategy is shown in (9), where, \( K_f \) is the frequency droop constant, and is provided to allow a certain degree of flexibility within the system. Also, there is one problem to keep in mind, that is the AC voltage of wind farm will sensitive to the DC voltage of HVDC link, which means the frequency control will operate only when the frequency changes exceeding a certain value to keep the system stable.

\[ U_{\text{dcref}} = U_{\text{dcN}} + K_f (f_s - f_{\text{set}}) \]

Increasing the gain tends to improve the transient response of the system. However, the steady state voltage deviation of the DC network increases which may exceed the permissible operating voltage limits.

5 Simulation results
Simulation models of HVDC system with wind farm collected and interconnected by diode based rectifier are developed on PSCAD/EMTDC platform. The topology has been shown in Fig. 1, and the parameters are listed in Table 1. As the diode-based rectifier is seen as a method of collection, the voltage of the whole system is relatively low but can be scale up if required.

5.1 Start-up procedures

Self start-up of wind turbines will work once the wind speed exceeds the start-up wind speed requirement (4 m/s). When the generator reaches a certain speed, the pitch angle is manually adjusted to 0° from 90° at a speed of 2°/s, which is neglected in the simulation. Once the generator speed reach to the nominal speed, it will be integrated into the grid. Fig. 10 shows the start-up of system. The DC voltage of the HVDC link is built first. After the self start-up of wind turbine, offshore AC voltage will be built by the grid-side converter. Then the circuit breaker of the diode-based rectifier is closed and the wind power can be transmitted to the onshore ac system. From Fig. 10, it can be seen that the wind system becomes stable in 2 s. Curves in Fig. 10 are the wind turbine rotor speed $\omega_m$, ac voltage $V_{Frms}$ and frequency $f_w$ at the collection point, active and reactive power $P_t$, $Q_t$ before the collection point, and the DC voltage of HVDC link $V_{dc}$.

From Fig. 11, it can be concluded that the system can be successfully started with the proposed strategy.

5.2 Steady state operation

The steady state operation is shown in Fig. 10 with the AC voltage $V_{Frms}$ and frequency $f_w$ at the collection point, $P_t$, $Q_t$ of the active and reactive power at the collection point of wind farm 1, $P_s$, $Q_s$ of the active power of the onshore VSC transmitted and the DC voltage of the HVDC link.

Wind farm 1 is connected to the system first and then wind farms 2 and 3 are connected to the DC link at $t = 12$ s. After all the wind farms being integrated into the system, an increase of wind speed happens at wind farm 1 at $t = 15$ s and results in a power output increase on the HVDC link. It can be seen that the system works well during the whole period of operation.

5.3 Frequency support

At $t = 50$ s, a load is integrated into the onshore AC system, leading to a frequency dip. Fig. 12 compare the results with and without frequency support when the load increases. As can be seen that, the output of wind power increases and the frequency goes back to the original value more quickly when frequency support is activated. As the quick response of wind turbine, the frequency $f_s$ only drop to 49.61 Hz compared to 48.75 Hz without frequency support.

Fig. 13 compare the results with and without frequency support when the load decreases. As can be seen that, the output of wind power decreases and the frequency goes back to the original value more quickly when frequency support is activated. As the quick response of wind turbine, the frequency $f_s$ only varies within 0.2 Hz, less than the result of without frequency support.

6 Conclusion

This paper studies the frequency support method for the AC system with diode rectifier HVDC system connected wind farms. Simulation models of the diode rectifier HVDC system and wind farms are built on PSCAD/EMTDC platform. Through simulation analysis, it shows that the utilization of active power reserve and diode rectifier HVDC system can provide frequency support for AC system.

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| Table 1 Parameters of the simulation system |
|--------------------------------------------|
| Components | Parameters | Values |
| wind system | power | 2 MW |
| | transformer | 0.69/35 kV |
| | switching frequency | 1.95 kHz |
| diode based Rectifier | transformer | 35/35/35 |
| | leakage inductance | 0.1 pu |
| onshore VSC | DC voltage | 90 kV |
| | power | 50 MW |
| | transformer | 40 kV/35 kV |
8 References

[1] Egea-Alvarez, A., Bianchi, F., Junyent-Ferre, A., et al.: ‘Voltage control of multiterminal VSC-HVDC transmission systems for offshore wind power plants: design and implementation in a scaled platform’, IEEE Trans. Ind. Electron., 2013, 60, (6), pp. 2381–2391

[2] Chen, X., Sun, H., Wen, J., et al.: ‘Integrating wind farm to the grid using hybrid multiterminal HVDC technology’, IEEE Trans. Ind. Appl., 2011, 47, pp. 965–972

[3] Gomis-Bellmunt, O., Junyent-Ferre, A., Sumper, A., et al.: ‘Control of a wind farm based on synchronous generators with a central HVDC-VSC converter’, IEEE Trans. Power Syst., 2011, 26, (3), pp. 1632–1640

[4] Torres-Oguin, R.E., Molinas, M., Undeland, T.: ‘Offshore wind farm grid integration by VSC technology with LCC-based HVDC transmission’, IEEE Trans. Sustain. Energy, 2012, 3, pp. 899–907

[5] Blasco-Gimenez, R., Ano-Villalba, S., Rodriguez-D'Derlee, J., et al.: ‘Distributed voltage and frequency control of offshore wind farms connected with a diode-based HVDC link’, IEEE Trans. Power Electron., 2010, 25, pp. 3095–3105

[6] Prignitz, C., Eckel, H.G., Achenbach, S., et al.: ‘FixReF: a control strategy for offshore wind farms with different WT types and diode rectifier HVDC transmission’, 2016 IEEE 7th Int. Symp. on Power Electronics for Distributed Generation Systems (PEDG), Vancouver, BC, Canada, 2016, pp. 1–7

[7] Morren, J., de Haan, S.W.H., Kling, W.L., et al.: ‘Wind turbines emulating inertia and supporting primary frequency control’, IEEE Trans. Power Syst., 2006, 21, (1), pp. 433–443

[8] Xu, G., Xu, L., Morrow, J.: ‘System frequency support using wind turbine kinetic energy and energy storage system’. Proc. 2nd IET Renewable Power Generation Conf., Beijing, China, 2013, pp. 1–4

[9] Ramtharan, G., Ekanayake, J.B., Jenkins, N.: ‘Frequency support from doubly fed induction generator wind turbines’, IET Renew. Power Gener., 2007, 1, pp. 3–9

[10] Liu, J., Yao, W., Wen, J., et al.: ‘Short-term frequency support of power system from wind farms with energy storage system’. 2015 IEEE Power and Energy Society General Meeting, Denver, CO, 2015, pp. 1–11

[11] Valsera-Naranjo, E., Sumper, A., Gomis-Bellmunt, O., et al.: ‘Design of a pitch control of a wind turbine to improve system frequency response’. 2009 13th European Conf. on Power Electronics and Applications, Barcelona, 2009, pp. 1–11

[12] Li, Y., Yang, Y., Li, Y., et al.: ‘Coordinated control of wind farms and VSC-HVDC to improve inertia level of power system’. Proc. CSEE, 2014, 34, (34), pp. 6021–6031 (in Chinese)

[13] Zha, R., Wang, Y., Li, X., et al.: ‘An additional frequency control strategy for interconnected systems through VSC-HVDC’, Autom. Electr. Power Syst., 2014, 38, (16), pp. 81–87 (in Chinese)

[14] Yao, W., Yang, M., Zhang, H., et al.: ‘VSC control and its modified algorithm for VSC-HVDC inverter participating grid’s frequency regulation’. Proc. CSEE, 2017, 37, (2), pp. 525–533 (in Chinese)

[15] Li, X., Zeng, Q., Wang, Y., et al.: ‘Control strategies of voltage source converter based direct current transmission system’, High Volt. Eng., 2016, 42, (10), pp. 3025–3037 (in Chinese)

[16] Yu, Y., Feng, Y., Jiang, H., et al.: ‘Research on VSC-MTDC for grid integration of wind farm’. Int. Conf. on Renewable Power Generation (RPG 2015), Beijing, 2015, pp. 1–5

[17] Datta, R., Ranganathan, V.T.: ‘A method of tracking the peak power points for a variable speed wind energy conversion system’, IEEE Trans. Energy Convers., 2003, 18, (1), pp. 163–168