Control of Dc Transmission System from a Wind Farm

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Abstract: Interest in the application of offshore wind farms is increasing due to the superior wind conditions in such locations. Wind power has an inherent characteristic in that the output power fluctuates due to wind velocity change. Leveled power generation is desirable not only for power systems, but also as a power source in a smart grid. If long distance transmission is required, then a dc link will be one solution. This paper treats a wind farm connected to a weak ac system through a dc transmission line with voltage source converters. Power levelling controls in the dc system are proposed and the effects of these controls are analyzed using the ATPDraw5 simulation program.

Keywords: Wind, power, generation, control, inverters

1. INTRODUCTION

Interest in the application of offshore wind power is increasing throughout the world. Offshore wind speeds obtained are typically higher than those onshore, so that higher power generation will be estimated (Ackerman, 2007). The proportion of wind power generation in the total power generation in Japan is smaller than that of other countries, due to the rarity of hilly areas with good wind conditions. Offshore wind farms are a feasible application for such countries, and are a useful power source for smart grids also. However, typical wind farms are directly connected to an ac power system; therefore, if long distance power transmission from the wind farm is required, dc cable transmission will be applicable. In this study, we consider dc power transmission from a wind farm. A robust and reliable wind power generator is required, especially for offshore application; therefore, a conventional squirrel cage type induction generator that has the simplest structure is assumed here. An ac voltage supply is required on the generation side, so that voltage source converters (VSC) are assumed for the dc power transmission because the VSC can supply ac voltage. We have proposed basic control for such a system that enabled stable power transmission of all generated power. (Noro, 2002, Tanomura, 2006) The generated power fluctuates depending on changes in wind velocity; therefore, power levelling is desirable for the receiving power system to relax stress on the generator governors. This paper proposes power levelling controls that are demonstrated by digital simulation using the ATPDraw5 program (Hoidalen, 2007). Frequency modulation on the generator side is taken into account for power levelling, which is quite different from a variable speed wind power generator (Pena, 1996, Datta, 2002).

2. WIND FARM AND DC TRANSMISSION

The configuration of the wind farm and dc transmission system considered in this study is shown in Fig. 1. The wind farm consists of 10 units of squirrel cage type induction generators with 1.25 MVA output rating. The voltage of the sending side ac bus, BUS-R, is 33 kV, and no synchronous generator is connected. The excitation voltage is supplied by the VSC inverter of the dc system. A local load of 500 kW is assumed on BUS-S. It is considered that this system is suitable for an offshore wind farm, because the squirrel cage induction machine is simple and robust. On the other hand, the VSC is complex equipment, but it can be enclosed in a sealed box to ensure the strength of the system, especially with respect to salt problems.

The rating of the dc transmission is 12.5 MW, 25 kV–500 A. A 50 km dc cable is assumed and VSC inverters with 6-arms full bridge pulse width modulation (PWM) are used on both sides.

Fig. 1. Wind farm with DC transmission line.

The receiving ac bus, BUS-R, is also 33 kV, and a short circuit power level of 40 MVA is assumed to represent a weak ac system. The weak ac system has voltage fluctuation problem for active power change. Better performance controlling ac voltage by VSC inverter is expected to be confirmed by applying the weak ac system.
3. MODELLING AND CONTROL

3.1 Wind data

Suitable wind data for simulation are not easily obtained, because available wind data are 5-minute average or longer time average values. Measurements were made at the top of an 18 m building at 1-s sampling intervals. The wind velocity measured over 3 h is shown in Fig. 2, and this was modified by adding 3.5 m/s to the measured velocity to compensate for low readings due to height and location.

![Wind velocity vs. time](image1)

**Fig. 2.** Wind velocity measured for the simulation.

The wind velocity data shown in Fig. 3 is a magnified part of Fig. 2 that was used for the simulation, and includes larger fluctuation rates. Wind generators receive different wind velocities in a farm and some power levelling effect is expected, but in this study the same wind velocity data was assumed for all generators that will give severe generation power change.

![Wind velocity vs. time](image2)

**Fig. 3.** Wind velocity used for the simulation.

3.2 Power system model for study

The capacity of the equipment used for the simulation is listed in Table 1. One squirrel cage induction generator is assumed to have a rating of 12.5 MVA, representing 10 units. The parameters of the generator are listed in Table 2 (Krause, 1986). The induction generator is modeled using a universal machine model in ATPDraw5, and mechanical torque calculated from the wind velocity data is applied to the shaft. A capacitor bank with 25% of the generator capacity is connected on the sending side ac bus, BUS-S. The inverters are modeled by ideal switches with the transient analysis of control systems (TACS) controlled on/off pulse signals. The receiving ac system is modeled by an R-L branch representing 40 MVA short circuit capacity. A capacitor bank with 20% of the dc link is assumed on both ac sides for reactive power supply and harmonic filtering.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power generation</td>
<td>12.5 MW, 660 V, representing 10 units</td>
</tr>
<tr>
<td>Transformer</td>
<td>12.5 MVA, 660 V/33 kV, 5% Z, Representing 10 units</td>
</tr>
<tr>
<td>DC link</td>
<td>Rating</td>
</tr>
<tr>
<td>Converter</td>
<td>VSC with PWM</td>
</tr>
<tr>
<td>Transformer</td>
<td>14 MVA, 33 kV/13.8 kV, 10% Z</td>
</tr>
<tr>
<td>Dc cable</td>
<td>2.8 Ω, 6 mH, 15 μF</td>
</tr>
<tr>
<td>Receiving side ac system</td>
<td>Short circuit power level</td>
</tr>
<tr>
<td></td>
<td>40 MVA, 33 kV</td>
</tr>
</tbody>
</table>

3.3 Control of the dc system

The control block of the sending side inverter is shown in Fig. 4. The constant frequency loop and ac voltage control consist of a basic combination proposed by the author (Tanomura, 2006). Constant frequency is obtained by a constant reference value of 50 Hz and an integrator; the output of the integrator becomes a phase angle θs, of the inverter output voltages. Ac voltage control is applied to maintain a constant generator bus voltage. Vref is a reference value and is used to compare with the bus voltage Vacs, and a proportional-integral (PI) control is also applied. The output of the PI controller, AMPs, is the amplitude of the inverter output voltage. The three phase voltage signals are calculated from AMPs and the phase angle θs. The three phase voltage signals are compared with a carrier wave and on/off pulses are determined in the PWM logic. A frequency of 2 kHz is used as the carrier wave. This control does not require any mutual control signal exchange between the inverters on both sides.

The added power levelling control on the sending side is shown by the frequency modulation part. This additional block measures the active power through the converter, Ps, and modifies the frequency represented by Δf, through a high pass transfer function, as shown in Fig. 4. When the wind velocity increases and the generation power increases, the ac bus frequency is increased by this control and reduces slip of
the induction generator and the output of the generator is reduced. As a result, power levelling will be obtained.

Control of the receiving side is shown in Fig. 5, which involves dc voltage control and ac voltage control as a basic control. Dc voltage control corresponding to conventional active power control maintains a constant dc voltage. This enables power conversion from the dc side to the ac side. When the dc voltage, \( E_d \), increases due to injected power from the sending side, this control advances the phase angle of the inverter voltage and increases the power through the receiving side inverter. This means that the dc voltage control is able to transfer active power from the dc side to the ac side. Ac voltage control is applied here with a PI function. The outputs of both controls, \( \Delta E_d \) and \( \Delta V \), are fed to the signal conversion block, and converted to an inverter voltage angle, \( \theta_r \), and an amplitude signal, \( \text{AMP}_r \). The three phase voltage signals are calculated from these two signals and the ac bus voltage angle \( \theta_{ac} \). The three phase voltage signals are fed to the PWM logic with a 2 kHz carrier wave. This control is a standalone type and requires no signal from the sending side inverter.

![Fig. 4. Control block for sending side inverter.](image)

![Fig. 5. Control block for receiving side inverter.](image)

The phase locked loop (PLL) detects the phase angle of the bus voltage, \( \theta_{ac} \). The PLL block shown in Fig. 6 (Sood, 2004) is defined by Eqs. (1), (2), and (3).

![Fig. 6. Block diagram for voltage phase detection.](image)

The active and reactive powers are calculated using the following equations.

\[
P = (V_a \times I_a) + (V_b \times I_b) + (V_c \times I_c)
\]

\[
Q = I_a(V_b - V_c) + I_b(V_c - V_a) + I_c(V_a - V_b)
\]

The signal conversion is placed here for simplicity, instead of a conventional \( d \) and \( q \) two axes conversion. Signal conversion directly outputs the amplitude signal and the phase angle signal of the inverter ac voltage from \( \Delta E_d \) and \( \Delta V \), as explained below. Figure 7 shows the power flow through the inverter transformer of the receiving side connected to the ac side with reactance \( X \) given per unit (pu). The power \( P_2 \) and \( Q_2 \) on BUS-R are given by the following well known equations.

\[
P_2 = \frac{V V_c}{X} \sin(\delta_1 - \delta_2)
\]

\[
Q_2 = -\frac{V V_c}{X} \cos(\delta_1 - \delta_2)
\]

Linearized equations are given as


\[
\begin{align*}
\Delta P_2 &= \frac{V_1 V_2 \cos \delta}{X} \Delta \delta + \frac{V_2 \sin \delta}{X} \Delta V_1 \\
\Delta Q_2 &= - \frac{V_1 V_2 \sin \delta}{X} \Delta \delta + \frac{V_2 \cos \delta}{X} \Delta V_1
\end{align*}
\]

where \(\delta = \delta_1 - \delta_2\). \(\Delta \delta\) and \(\Delta V\) are solved from Eqs. (8) and (9) as follows.

\[
\begin{align*}
\Delta \delta &= \frac{X \cos \delta}{V_2} \Delta P_2 - \frac{X \sin \delta}{V_2} \Delta Q_2 \\
\Delta V_1 &= \frac{X \sin \delta}{V_2} \Delta P_2 + \frac{X \cos \delta}{V_2} \Delta Q_2
\end{align*}
\]

Equations (10) and (11) are represented in Fig. 8.

![Signal conversion](image)

Fig. 8. Signal conversion.

Typical operation conditions have \(V_1 = 1.0\) pu, \(V_2 = 1.0\) pu, \(P_1 = 1.0\) pu, and \(Q_2 = 0.0\) pu. The impedance of the transformer \(X = 0.1\) pu, the angle \(\delta = 0.10\) rad is obtained from Eq. (6), then \(\cos \delta = 1.0\) and \(\sin \delta = 0.1\) can be applied. The simplified conversion block is replaced by Fig. 9. Figure 9 has only simple gain \(X = 0.1\) and \(X^2 = 0.01\). The signals \(\Delta Ed\) and \(\Delta V\) correspond to \(\Delta P_2\) and \(\Delta Q_2\) respectively. This signal conversion results in decoupled control between the active and reactive powers.

![Signal conversion in ATPDraw5](image)

Fig. 9. Signal conversion in ATPDraw5.

New additional dc voltage control is shown in Fig. 6, which modifies the dc voltage control reference value by \(\Delta Edref\) to obtain power levelling flows through the inverter and permits dc voltage change. The stored energy in the dc side is represented by \(1/2CEd^2\), where \(C\) is the total capacitance in the dc circuit and \(Ed\) is the dc voltage. This means that the energy in the dc circuit can be controlled by changing the dc voltage. When the power is injected from the sending side and this additional control raise the dc voltage, the active power output to the receiving ac system is reduced and it will contribute to power levelling.

4. SIMULATION

The effect of the proposed power levelling scheme was tested by simulation using the ATPDraw5 program. The step time of 2 \(\mu\)s is used in the calculation. The initial interval during 2 s is used to obtain steady state operation, and the wind velocity change is started from \(t=3\) s. The calculated results between \(t=2\) s and \(t=22\) s are plotted.

4.1 Basic control

The simulation results for basic control without power levelling controls on both sides are shown in Fig. 10. Figure 10(a) shows the active powers on both sides, where \(P_1\) is the sending side and \(P_2\) is the receiving side (in pu), based on 12.5 MVA. The sending side active power \(P_1\) changes similar to the change in the wind velocity pattern.

![Basic control](image)

Fig. 10. Basic control.
The receiving side active power $P_2$ also changes similar to the wind velocity change, but is smaller than $P_1$ due to losses. Figure 10(b) shows the reactive power of both inverters. In this simulation, the reactive power on both sides stays within 20% of the inverter capacity. Figure 10(c) shows the dc voltage that is controlled around 1 pu. Figure 10(d) shows the ac voltages on both sides, which are well controlled and have overlapping curves. These results reveal that the basic combination of controllers on both sides provides stable operation in this system. PIs with $10+10/s$, and $200+20/s$ are used as ac voltage controllers for the sending side and the receiving side, respectively. A PI with $0.5+5/s$ is used for the dc voltage controller.

4.2 Frequency modification on the sending side

Figure 11 shows the effect of frequency modification on the sending side. Figure 11(a) shows the active powers, $P_1$ and $P_2$. The change of active powers $P_1$ and $P_2$ becomes very slow compared with that in Fig. 10. Therefore, it is considered that the desired power levelling is obtained. This slow change of active power will be followed by the governors of typical synchronous generators in power systems. The change of reactive powers in Fig. 11(b) is similar to Fig. 10. In addition, the dc voltage changes shown in Fig. 11(c) stay in a narrow band. The frequency deviation shown in Fig. 11(e) is less than +/-2 Hz. The problem is whether or not this frequency deviation is acceptable. However, +/-2 Hz is a large deviation in a conventional ac system; therefore, we assume only an induction generator in the sending side, so that this frequency deviation will be acceptable. The local load on BUS-S will suffer from this deviation; therefore, some confirmation will be required in actual application. The parameters $K_1=30$ (Hz/pu) and $T_2=5$ s are applied here.
4.3 Dc voltage modification on the receiving side

Figure 12 shows the results for application of the dc voltage modification on the receiving side. The active power on the sending side in Fig. 12(a), $P_1$, changes in the same way as that in Fig. 10. The active power on the receiving side, $P_2$, is modified and its rate of change is lowered compared with that in Fig. 10. The power levelling by this controller is limited to short time and is therefore insufficient. The dc voltage shown in Fig. 12(c) has a large change and reaches approximately 1.5 pu, which would cause possible insulation problems. The parameters $K_2=2$ (pu/pu), and $T_2=2$ s are used.

![Graphs of active power, reactive power, dc voltage, ac voltage, and frequency change](image)

(a) Active power (pu)  
(b) Reactive power (pu)  
(c) Dc voltage (pu)  
(d) Ac voltage (pu)  
(e) Frequency change (Hz)

Fig. 13. Frequency modulation and DC voltage modulation.

4.4 Application of both modifications

Figure 13 shows the results with application of modifications on both sides. The sending side active power $P_1$, in Fig. 13(a) has almost the same shape as that in Fig. 11 and a power levelling effect is obtained. However, the receiving side active power $P_2$ has a slightly more smoothed shape than that shown in Fig. 11. The dc voltage in Fig. 13(c) deviates largely, similar to that in Fig. 12(c). The frequency change in Fig 13(e) is almost the same as that in Fig. 11(e). A multiplier effect is expected by the application of both additional controls; however, this result indicates that only a small effect is obtained, and effects on both side additional controls seem to have independent.

The results indicate that the frequency modulation on the sending side has a large effect, and the dc voltage modulation has a small effect for power levelling through the dc transmission system. The energy stored in the dc circuit depends on the capacitance; therefore, connection of larger capacitor in the dc circuit should be considered for effective power leveling.

5. CONCLUSIONS

Power levelling for a dc transmission system connected to a wind farm was proposed and investigated by simulation. However, it requires several deviations from rating values on frequency or dc voltage, it will be one of feasible measures. Application of a larger capacitor in the dc circuit will be a future work of this study.

REFERENCES


