Control strategy to improve power transmission capacity from wind farms to weak AC grids

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Abstract — With the increasing connection of large wind farms based on direct driven Permanent Magnet Synchronous Generators (PMSGs) to weak AC grids, the steady state characteristics of such wind farms, particularly those connected to very weak AC systems with a Short Circuit Ratio (SCR) of 1, are important factors for analysis with a view to improvement. In this paper, the issue is thus analysed in order to identify the factors limiting transfer capability from wind farm output. This paper thus presents a simulation model of a wind farm connected to a very weak AC grid, and a vector control strategy is used with respect to the full power converters of the wind farm in order to track current order injected from the converters into the AC system. A supplementary outer loop control is proposed to support grid voltage and to maximise transferred power into the very weak AC grid, based on a droop gain which is allowed to update the reactive power reference for reactive power control for the grid side converter based on changes to the output of the wind turbine, within grid code requirements. The simulation results prove that the proposed control system offers a promising method for addressing challenges arising in active power transmission, and thus increasing transferred active power from such wind farms to very weak grids.

1. INTRODUCTION

Wind energy systems have become crucial factors in research into renewable energy sources, and thus the need to assess the impact of wind generation on the performance of AC grids or, conversely, to analyse the effect of AC grid connections on wind farm performance is important. The variability of wind power generation and grid voltage fluctuations and frequency deviations are the main challenges that arise on connecting wind farms to AC grids, especially weak AC grids. The strength of AC grids is measured by their Short Circuit Ratio (SCR). Standard values SCR in high voltage areas are greater than 3 (strong grid), less than 3 and greater than 2 (weak grid), and less than 2 (very weak) [1] Weak AC grids are more sensitive to changes in import/export of real and reactive power to and from the grid than strong AC grids, as these changes cause significant deviations in grid voltage. Thus, the specification of AC grids must be taken into consideration when developing connections to wind farms for use during steady state and transient conditions. However, the selection of appropriate types of wind turbine technology is also necessary.
Recent trends in the wind industry have led more wind turbine designs to consist of full power converters between the generator and the AC grid [2]. This allows turbine to operate at variable speeds as well as giving the wind farm the capability to regulate reactive power freely within the limits of the power converter, making it better able to support AC grids [3]. A direct driven permanent magnet synchronous generator (PMSG) topology is more attractive for wind turbine manufacturers, as this requires less frequent maintenance and does not have a rotor current, thus increasing efficiency [4]. The control strategy used in wind farm converters is also very important for successful integration into AC grids. The vector current control strategy predominantly used in industrial practices has the capability of limiting the current flowing into the converter and offers efficient decoupling of the active and reactive power control, However, this strategy of control has been found by several researchers to work poorly for very weak AC grids (i.e., high impedance grids). In terms of transmission power, the maximum power that can usually be transmitted to an AC grid has an SCR of 1.0 is 0.4pu in order to maintain converter stability [5]. In [6], it was stated that, with a significant tuning effort, the active power capability could be increased to 0.5pu to preserve the converter stability under very weak grid conditions of SCR=1. With the optimisation of the controller parameters of the grid side converter, the transferred power might reach 0.6pu [7].

In this paper, the power transfer limits of wind farms connected to very weak AC grids is analysed to investigate the main factors affecting these limits. A wind farm based on variable speed wind turbines connected to a very weak AC grid is modelled, and the effectiveness of a proposed control in terms of transmitting more active power from the wind farm into a very weak AC grid is validated by simulation using the PSCAD simulation tool.

2. POWER TRANSMISSION LIMITATIONS

A wind farm based on PMSGs is connected to a weak AC grid by means of a back to back VSC converter. Thus, the limitations of weak AC grids and power converters are both important issues affecting power transmission limitations.

2.1. Grid Limitation

Figure 1 illustrates a wind farm connected to an AC power grid with transmission impedance $Z_g$. The voltage of the AC grid is $V_g$, while the voltage at a remote point can be taken as a constant $V_s$.

The active and reactive power of the grid side inverter are $P$ and $Q$, respectively.

![Figure 1. A simple system for wind farm to AC grid.](image)

The short circuit power level in MVA is defined as

$$ S_{sc} = \frac{V_s^2}{Z_g} $$  \hspace{1cm} (1)

The grid current, $I_g$, is

$$ I_g = \left( \frac{S}{V_g} \right)^* = \frac{P - jQ}{(V_g)^*} $$  \hspace{1cm} (2)

The voltage difference, $\Delta V$, is thus
\[ V_g - V_s = \Delta V \]  
\[ \Delta V = Z_g I_g = (R_g + jX_g) \left( \frac{P - jQ}{V_g} \right) = \frac{R_g P + X_g Q}{V_g} + j \frac{X_g P - R_g Q}{V_g} \]  

Substituting (4) into (3), yields

\[ V_g = V_s + \frac{R_g P + X_g Q}{V_g} + j \frac{X_g P - R_g Q}{V_g} \]  

Multiplying both sides of equation (5) by \((V_g)^*\) then yields

\[ V_g (V_g)^* = V_s (V_s)^* + R_g P + X_g Q + j (X_g P - R_g Q) \]  

Equation (4) makes it clear that \(\Delta V\) is related to the impedance of the grid and the real and reactive power output of the wind farm. Higher levels of transmission impedance \(Z_g\) result in larger voltage variations then small impedances.

The magnitude of grid voltage can be determined according to following equations.

\[ V_g = |V_g| e^{j\delta} = |V_g| \cos \delta + j |V_g| \sin \delta \]  

where \(\delta\) is the angle of AC grid voltage. Substituting (7) into (6) thus yields

\[ |V_s|^2 = V_s |V_s|^2 \cos \delta + R_g P + X_g Q + j(X_g P - R_g Q - V_s |V_s| \sin \delta) \]  

Equating the real and imaginary parts of both sides of equation (8) then yields

\[ |V_s|^2 = V_s |V_s|^2 \cos \delta + R_g P + X_g Q \]  

and

\[ 0 = X_g P - R_g Q - V_s |V_s| \sin \delta \]  

From equation 10

\[ Q = \frac{X_g P - V_s |V_s| \sin \delta}{R_g} \]  

By solving equations (9) and (11) and extracting \(P\) from the solution,

\[ P = \frac{|V_g|^2}{R_g^2 + X_g^2} \left[ R_g |V_s| - V_s R_g \cos \delta + V_s X_g \sin \delta \right] \]  

Equation (12) shows that, the quantity of active power transfer that can be delivered into the AC grid is mainly limited by the AC grid impedance. Additionally, the active power delivered to the grid depends on the angle of the AC grid voltage.

### 2.1.1. Angle Stability Limit

The power transfer is limited by the angle of grid voltage. Figure 2 shows a plot of equation (12), demonstrating that the active power level depends on angle \(\delta\) for different grid resistance values where
$X_g$ remains constant at a value of 1pu. The SCR is inversely proportional to grid reactance $X_g$, and any reduction of resistance value limits the power transferred into a weak AC grid.

Figure 2. Transferred active power for different grid resistance values ($V_g=1$pu).

Figure 3 shows the transferred active power depending on the angle $\delta$ for different SCRs where $R_g$ is kept constant at 0.01pu. It can be seen that the amount of active power is limited at low SCRs and that the angle impact should be taken into account for very weak AC grids [8].

Figure 3. Transferred active power for different grid reactance values ($V_g=1$pu).

2.1.2. Voltage Stability Limit

To study voltage stability limits, equations (9) and (10) can be solved to obtain the magnitude of grid voltage as a function of power flows and grid impedance:

$$
\left|V_g\right| = \sqrt{\frac{V_s^2 + 2\left(R_g\cdot P + Q\cdot X_g\right) + \left[V_s^4 + 4\left(R_g\cdot P + Q\cdot X_g\right) - 4\left(X_g\cdot P - R_g\cdot Q\right)^2\right]}{2}}^{1/2}
$$

(13)
If the reactive power is extracted from equation (13) to find the voltage operational area for a given grid voltage,

\[ Q = \frac{1}{R_g^2 + X_g^2} \left( \left| V_g \right|^2 X_g - \left[ \left| V_g \right|^2 \left( 2R_g P + V_s^2 \right) \left( R_g^2 + X_g^2 \right) - \left| V_s \right|^2 R_s^2 - P^2 \left( R_s^2 + X_s^2 \right)^2 \right]^{1/2} \right) \]  

(14)

Figure 4 shows the PQ curve of the system under different SCRs with a grid voltage of 1pu. Very weak grids need more reactive power to support the grid voltage and accommodate more active power. In addition, the required reactive power depends on the grid voltage level.

Figure 5 shows the PQ curve for a very weak AC grid with SCR=1 and the grid voltage limits with ±10% of the nominal value of 1pu. The maximum acceptable grid voltage limit requires more reactive power compared to the minimum limit.

According to the British Grid Code, where the wind farms are connected directly to the AC transmission system at 132kV, such wind farms must be able to deliver a rated MW output at any point between the limits of a 0.95 leading power factor and a 0.95 lagging power factor at the connection point with the AC transmission system. This means that wind farms must export/import reactive power of ±0.33 pu [9]. In addition, the grid codes require that each wind farm to have the capability of controlling the voltage at the connection point with the AC transmission system. Thus, during a reduction of AC transmission, a wind farm should be capable of being provided with active power, in proportion to the acceptable limits of its voltage and the maximum limits of the reactive current of the AC transmission system, without exceeding the wind turbine generator limit.
2.2. Power Converter Limitations

2.2.1. Thermal Limits
Thermal limits refer to the thermal capabilities of the converter switching valves. An increase of converter active power results in increased converter current, which could lead to thermal damage of the converter. Thus, the maximum current of the converter should be designed to supply nominal power in a steady state to protect the switching valves [10].

2.2.2. Converter Requirements
Typically, a series inductor is utilised as the filter between the power converter and the AC grid. A high inductance is required to reduce current harmonic distortion to improve the dynamic response of the system, However, high values of inductance limit the capability of the power converter [10].

3. CONFIGURATION SYSTEM MODEL
In this section, the PMSG wind turbine model used is described along with the proposed control strategy for the back to back power converter, wind farm, and AC grids.

3.1. Modelling of Wind Turbines

The standard model of a wind turbine is used, where the output of the wind turbine can be written as

$$P_{turbine} = \frac{1}{2} \rho \pi r^2 C_p V_w^3$$

where $\rho$ is the air density in kg/m$^3$, $r$ is the radius of the wind turbine rotor m, $C_p$ is the power coefficient, and $V_w$ is the wind speed in m/s. The $C_p$ is defined by the following formula.

$$C_p = \frac{1}{2} \left( \frac{\lambda - 5.6 - \frac{\beta^2}{45}}{\lambda} \right) e^{-\frac{\lambda}{5}}$$

where $\lambda$ is the tip speed ratio of the wind turbine, $\beta$ is the blade angle with wind speed, $\lambda = \frac{2.237 V_w}{\omega H}$, and $\beta = 0$ in order to capture the maximum power [4].

Figure 5. The PQ curve for different grid voltages (SCR=1).
3.2. Modelling of Permanent Magnet Synchronous Machines

The PSCAD/EMTDC software library offers a model of PMSG as described in the following equations [11].

\[ V_q = r_s \cdot i_q + L_q \frac{di_q}{dt} + L_{dq} \cdot i_d \cdot \frac{d\theta_r}{dt} \]  
(17)

The voltage equations from the main stator windings in d-q reference frame are

\[ V_d = r_s \cdot i_d + L_d \frac{di_d}{dt} + L_{dq} \cdot i_q \cdot \frac{d\theta_r}{dt} \]  
(18)

where \( L_q, L_d \) are the quadrature and direct axes stator winding inductance in pu, \( r_s \) is the stator winding resistance in pu, and \( \theta_r \) is the position of the rotor d-axis with respect to the magnetic axis of phase (A) winding in rad. The motion equation of generator is thus written as

\[ J \frac{d\omega_m}{dt} = T_m - T_e - B\omega_m \]  
(19)

where \( J \) is the total moment of inertia in kgm\(^2\), \( \omega_m \) is the turbine speed in rad/s, \( B \) is the friction coefficient, \( T_m \) is the mechanical torque of the turbine in Nm; and \( T_e \) is the generator electromagnetic torque in Nm.

3.3. Model of Back to Back Converters

The PMSGs are linked to the AC grid through back-to-back converters, and vector control techniques can be used to control converter operation [12]. Two vector control schemes are thus considered for the generator-side and grid-side converters. The grid-side converter is used to regulate the DC voltage and control reactive power delivered to the AC grids, while the generator-side converter regulates the PMSG speed to achieve the desired power transfer under given wind conditions [10].

3.3.1. Generator Side VSC Controllers

Figure 6 shows a block diagram of the generator side converter control. The dynamic model of converter in the synchronous d-q reference frame is described by the following equations:

\[ V_{ds} = R_i \cdot i_{ds} + L \frac{di_{ds}}{dt} + \omega_m L i_{qs} + V_{cd} \]  
(20)

\[ V_{qs} = R_i \cdot i_{qs} + L \frac{di_{qs}}{dt} + \omega_m L i_{ds} + V_{cq} \]  
(21)

where \( V_{ds}, V_{qs}, i_{ds} \) and \( i_{qs} \) are the instantaneous stator voltages and currents in the dq-axes reference frame, \( V_{cd}, V_{cq} \) are the instantaneous converter voltages in the dq-axes reference frame, \( \omega_m \) is the electrical angular speed of the rotor in rad, and \( R \) and \( L \) are the inductance and resistance of converter filter, respectively. In order to design a generator speed control, Equation (19) is rewritten as [13].
The electrical torque of the generator can be expressed as

\[
\frac{d\omega_m}{dt} = \frac{T_m - T_e - B\omega_m}{J}
\]  

where \( p \) is the pole pair number, and \( \psi \) is the rotor magnetic flux generated by the permanent magnet in Wb. According to equations (22) and (23), the speed regulator generates the reactive current reference, whereas the active current reference is generated by the reactive power controller [12]. Thus, the converter reactive current is used to regulate the angular speed of the wind generator to the reference speed \( (\omega^* = 0.6 \text{ pu}) \), which in turn regulates the active power to the grid side converter; active current is used to regulate the reactive power to zero \( (Q^* = 0) \). Proportional integral (PI) controllers were used to minimize the error between the reference and the measured variables to zero. The proportional gain \( K_P \) and integral gain \( K_I \) are further explained in Appendix A.

![Diagram](image_url)

**Figure 6.** Block diagram of generator side converter control.

### 3.3.2. Grid Side VSC controllers

The major control functions of the grid-side converter, shown in Figure 7, are to regulate the DC link voltage and the reactive power to the AC grid. A Phase-Locked Loop (PLL) is employed to create synchronisation between the converter and grid. The dynamic model of the grid connection in the d-q rotating reference frame is thus

\[
V_{dg} = V_{cd} - R_i_{dg} - L \frac{di_{dg}}{dt} + L\omega_m i_{qg}
\]  

\[
V_{qg} = V_{cq} - R_i_{qg} - L \frac{di_{qg}}{dt} + L\omega_m i_{dg}
\]
An outer DC voltage control is used to set the direct current reference for the active power control, by regulating the DC voltage to its reference value, maintaining the balance of AC/DC power transformation between the generator and grid converters [4].

Reactive power control is achieved by controlling the reactive current reference, while a power droop control is used to regulate the injected reactive power from the grid side converter to support the weak AC grids voltage. In the proposed control, the Q reference of the reactive power control is updated according to the error of wind turbine output ($P_{wt} - P_{wt}^*$), while the power droop ($D$) constant is calculated as

$$\Delta Q = D \Delta P$$

is calculated as

$$Q_{Max}^* - Q_{Min}^* = D \left( P_{wt}^* - P_{wt} \right)$$

or

$$Q_{Max}^* - Q_{Min}^* = D \left( P_{wt}^* - P_{wt} \right)$$

where $Q_{Max}$ and $Q_{Min}$ are the maximum and minimum reactive power references, and $P_{wt}$ and $P_{wt}^*$ are the measured and reference wind turbine power respectively. To meet grid code standards, the maximum reactive power reference is $Q_{Max} = 0.33pu$ at the maximum error of wind turbine output. The minimum reactive power reference is similarly $Q_{Min} = 0$ where the error of the wind turbine output equals 0. As any increase of wind generation leads to a significant reduction in weak grid voltage, the wind farm should provide reactive power to support weak voltage within the limits of the reactive power reference.

![Figure 7. Block diagram of grid side converter control.](image)

3.4. Aggregated Wind Farm Model

An aggregated wind farm model is used to reduce the complexity of the analysis. Such a wind farm is comprised of a number of wind turbine generators with identical characteristics, usually rated at a low voltage output (690V). The voltage is stepped up to medium (33kV) by a transformer located at each wind turbine generator. These wind turbine generators are connected in parallel in a group, and each group is connected to the collection system and then to the AC grids through a step up transformer to reach transmission level (132 kV) [14].
3.5. AC Grid Model

The AC grid is modelled as a voltage source behind Thevenin impedance. The weak grid condition is simulated by high impedance between Bus 3 and Bus 4, as seen in Figure 8.

4. SIMULATION AND ANALYSIS

A simulation is applied in this paper to analyse the issues with increasing wind power generation. Fig. 8 shows the test system diagram. The system has 4 buses operating at the voltages of 33 and 132kV, and the 33kV wind farm bus is connected to the weak AC grid at 132kV by a collector cable and a 33/132 kV transformer. The short circuit ratio of weak AC grid is 1 at the connection point with the wind farm, which is a 200MVA wind farm comprised of 40 PMSGs. The technical parameters of the test system are included in Appendix A.

![Figure 8. Test system.](image)

4.1. Wind Power Transfer Limit

Figure 9 shows the maximum transferred power to a very weak AC grid with a constant reactive power reference. When the reactive power reference is 0pu, the amount of transferred active power is 0.35pu, whereas the transferred active power is 0.685pu where the reactive power reference is 0.33pu at a grid voltage of 0.9pu. However, using a reference reactive power equal to 0.33pu increases the grid voltage beyond the maximum operational limit of 1.1pu during low wind farm output periods. Thus, reactive power should be injected at such times according the magnitude of the output of the wind farm to support the weak AC grid voltage within acceptable limits and to improve the performance of the system.
4.2. Wind Power Transfer Limit with Proposed Control

When the wind speed increases, the output power of the wind turbine increases to 0.9pu, as shown in Figure 10, and the active power of wind farm increases to 0.73pu, as shown in Figure 11. This increase is greater than achieved in the literature (0.5 and 0.6 pu). As a result of this increase, grid voltage is supported by generating reactive power from the grid side converter. The response of the reactive power controller, shown in Figure 12, reveals that the reference and measured reactive power levels track each other; in addition, the voltages of the wind farm and weak ac grid are within acceptable limits, as shown in Figure 13.
Figure 11. Wind farm output.

Figure 12. Measured and reference reactive power of grid side converter.

Figure 13. Grid and wind farm voltages.
5. CONCLUSIONS

The impedance and voltage angles of AC grids comprise theoretical limitations on the maximum active power that the wind farms transmit to the AC grids especially in very weak AC grids. The proposed control is suitable to utilize the capability of the wind farm to maintain the very weak AC grid voltage within acceptable limits during the increase of wind power generation. Additionally, the maximum transferred power is increased around 10% into AC weak grid with SCR equal to 1 what has been achieved literature.

Appendix A:

| Generator side converter | Grid side converter |
|--------------------------|---------------------|
| **Inner loops**          |                     |
| \( id \) current         | \( k_p = 3, k_i = 300 \) |
| \( iq \) current         | \( k_p = 3, k_i = 300 \) |
| **Outer loop**           |                     |
| Speed control            | \( k_p = 0.5, k_i = 25 \) |
| Reactive power control   | \( k_p = 0.5, k_i = 25 \) |
| \( L; R \) (Converter filter), \( C \) (DC-link) | 105 mH, 0.001Ω, 20000 μF |
| Switching frequency      | 1650Hz              |
| Technical parameters of test system |                   |
| \( R_1 \) 0.055 ohm      | \( R_2 \) 0.8702 ohm |
| \( L_1 \) 0.0055mH       | \( L_2 \) 0.2773 H |

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