Generator Technologies

Issue #WP102: Technical Information from Cummins Generator Technologies

Benefits and challenges of a grid coupled wound rotor synchronous generator in a wind turbine application

White Paper

Ram Pillai

Sridhar Narayanan

George Swindale

Abstract

There is a need for very large wind turbines in order to meet the increasing demands from renewable energy sources. A directly coupled synchronous generator with a variable transmission is one of the options for very large wind turbines. This wind turbine topology benefits from harmonic free, transformer free, better fault current contribution and greater reliability.

However, there are challenges associated with the topology, such as low voltage ride through performance and complex gearbox arrangements.

I. Wind turbine topologies

Wind turbine size and technologies have been developed rapidly over the last decade (Figure 1).

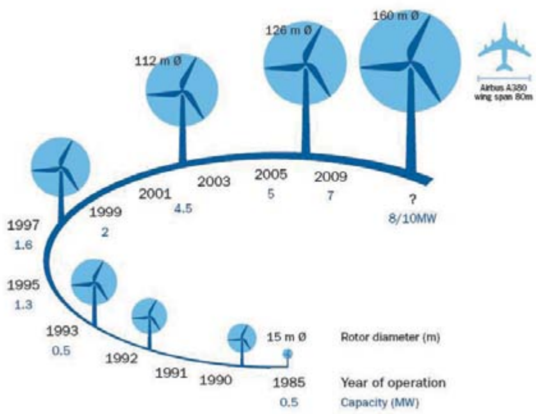


Figure 1: Size of wind turbines over time [1]

Until 2000, most wind turbines were based on cage induction generators that are directly connected to the grid, as shown in Figure 2. The rotational speed of the rotor is essentially fixed and the rotational speed varies only by a few percentage points. These fixed speed induction generator (FSIG) wind turbines have the advantages of being simple, reliable and well proven. However, FSIG wind turbines suffer from a number of disadvantages. Firstly, fixing the rotor speed generates high mechanical loading on the structure. Secondly, FSIG wind turbines cannot maintain maximum aerodynamic efficiency. Finally, FSIG turbines are not grid friendly in terms of reactive power, low voltage ride through and flicker. For these reasons an FSIG drive train is no longer favourable for large wind turbines.

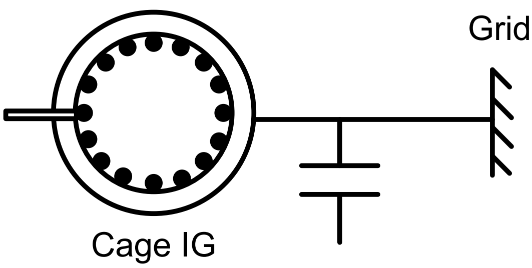


Figure 2: FSIG wind turbine

The rotational speed range of an induction generator can be improved by increasing the rotor winding resistance. Variable slip wind turbines use this technique to allow their rotor speed to change by employing external resistors, as shown in Figure 3. Increasing the rotor resistance stretches the speed range and thus allows the turbine to increase the speed by 10%. Heat loss in the external resistor, limited speed range and poor grid performance are some of the limiting factor for large turbines with a variable slip arrangement

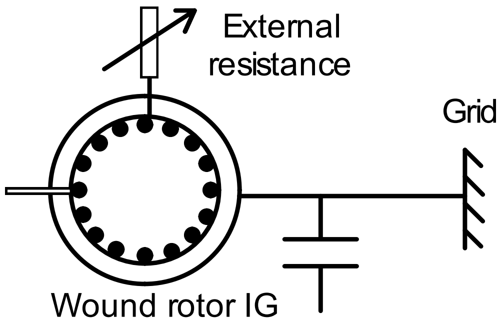


Figure 3: Variable slip wind turbine

Until recently, the Doubly Fed Induction Generator (DFIG) has been the most common solution for variable speed wind turbines. Connecting a four quadrant (4Q) converter to the rotor windings enables the control of both the generator torque and reactive power flow (see Figure 4). The rotor speed can be changed by absorbing or injecting rotor active power by the converter. The typical speed range of DFIG is ±30% around synchronous speed. It is generally understood that the rotor side converter power rating is 30% of the generator rating. This is because only part of the active power flows through the rotor circuit. However, increased demand in reactive power controllability, wider speed range and low voltage ride through requirements results in an oversized converter.

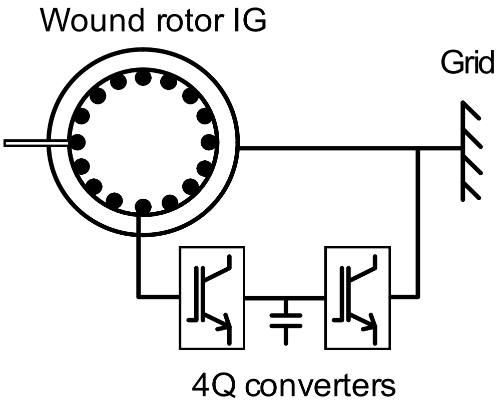


Figure 4: DFIG configuration

Increased wind turbine size and demanding grid code requirements lead to an even wider speed range for wind turbines employing two fully rated 4Q converters. In this topology, the converter is connected between the generator and the grid, as shown in Figure 5. The generator of this topology can be either a synchronous or an induction generator. The rating of the converter has to be the rating of the generator as the total generator power goes through the converter.

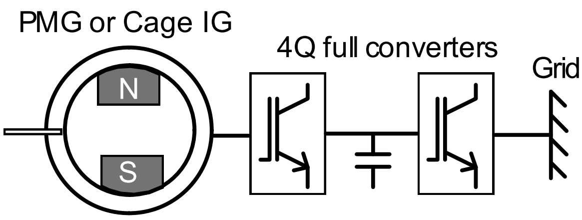


Figure 5: 4Q fully rated converter configuration

Back-to-back voltage source converters decouple the generator from the grid and the thus the electrical frequency of the generator can be changed independently from the grid. Any grid disturbance does not impact the generator directly. Therefore, effective control actions can be made to provide additional reactive power support to the grid in the event of a grid voltage drop. Wider speed ranges of the fully rated converter wind turbines manages to reduce the mechanical loading significantly as well as improve the grid friendliness. These technical advantages allow the design of very large wind turbines to meet the current demand for renewable power generation.

Instead of using a 4Q converter for the generator, a passive diode rectifier can be used with a wound rotor synchronous generator, as shown in Figure 6 However the grid side converter has to be a four quadrant inverter in this topology.

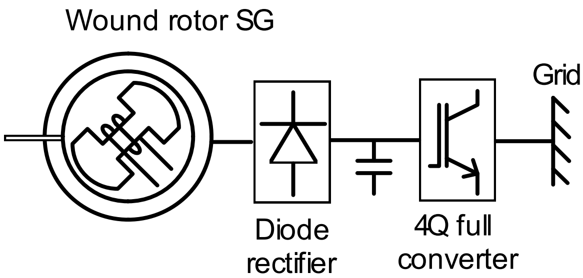


Figure 6: Fully rated diode rectifier in a wind turbine

II. Grid coupled synchronous generators with variable transmission

Wound rotor synchronous machines are the primary source of electricity generation in the grid. Performance of a synchronous generator has been well understood for centuries and the power system infrastructure is designed around this principle. Consequently, using a directly coupled wound rotor synchronous generator for wind turbines has several benefits.

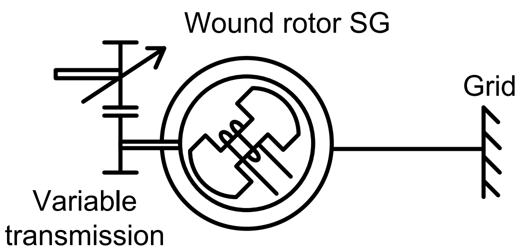


Figure 7: Directly coupled synchronous generator

A synchronous generator can be directly connected to the grid as shown in Figure 7.
A variable transmission is used to decouple the mechanical speed of the generator from the wind turbine rotor. This allows the wind turbine rotor speed to vary while the generator rotor is fixed to the grid frequency.

2.2 Benefits

2.2.1 Reactive power control capability

Typical PQ (real power 'P' and reactive power 'Q') capability curve of a wound rotor synchronous generator is shown in Figure 8. Control of reactive power is vital for the grid voltage stability and a wound rotor synchronous generator wind turbine is proven to provide this essential support to the grid.

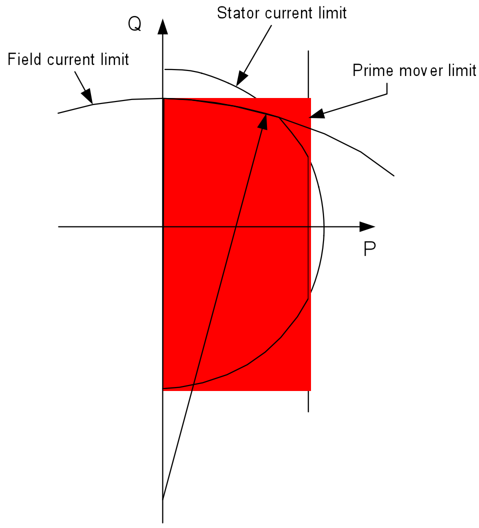


Figure 8: PQ capability chard of a synchronous generator

2.2.2 Harmonic free

Power electronic converters produce pulse width modulation (PWM) voltage waveforms while the grid voltage is sinusoidal. This results in current harmonic injection into the grid. Harmonic currents from the converter could resonate with the power system components and could lead to component failures. For example, a wind farm network consists of several capacitive components such as cables and capacitor banks. These capacitive components suffer from converter switching harmonics. Generally, harmonic filters are used to eliminate the switching frequencies but harmonic filters lead to additional power losses.

On the other hand, using a direct coupled synchronous machine generates sinusoidal waveforms and the harmonic interference is totally eliminated from the system. In addition there is no need for harmonic filters in the wind farm.

2.2.3 Transformer free

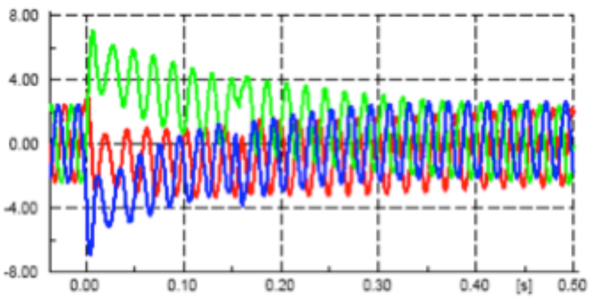
Employing a converter for a wind turbine requires a transformer for each wind turbine to step up the wind turbine voltage to the wind farm network voltage. This is because the semiconductor switches used for the converters have voltage limitations. Multi-level converters are used for the wind turbines but they are still not enough to meet the distribution voltage. This voltage has to be stepped up by transformer to match the wind farm's network voltage.

Voltage rating of 11kV and 33kV are typical values for a multi-megawatt wound rotor synchronous generator. Therefore, there is no need for a transformer for each wind turbine to connect to the grid.

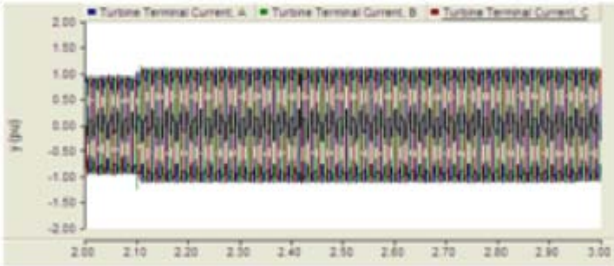
2.2.4 Fault current contribution

Significant penetration of converter based wind turbines has led to concerns about the impact on the operation of the protection system. In particular, the limited fault current capability of the converter could lead to malfunctioning of the protection system which largely relies on overcurrent based protection techniques [2].

Synchronous generators provide enough fault current to operate the protection system and the fault current's typical variation is shown in Figure 9a. On the other hand, the converter only provides a small amount of fault current contribution (see Figure 9b) as the current is limited by the converter protection system. It is common to design a 4Q converter with only 10% overload capability above rated [3].



(a) Fault current of a synchronous generator



(b) Fault current of a full converter [3]

Figure 9: Fault current contributions

2.2.5 Reliability

Eliminating the power electronic converter and transformer from a wind turbine improves reliability, as the number of components in the system is reduced. However, a variable transmission is added to the system. If the variable transmission is assumed to be reliable then the overall reliability of the wind turbine will improve.

2.3 Challenges

2.3.1 Low voltage ride through

The design of synchronous generators for low voltage ride through involves understanding its effects on the generator and its components. While full power converters and high inertia accessories can aid with complying with the low voltage ride through requirements from grid codes, the stress involved with a typical event needs to be understood to ensure a robust generator design. The following components are more likely to be impacted during a low voltage ride through, and hence care must be taken to include sufficient safety margins into the design.

a) Stator windings: Low voltage ride through and the aftermaths of it (re-synchronizing into the grid) involve large currents flowing through the stator windings. These currents induce electromagnetic forces on the stator windings which lead to their movement and could potentially lead to mechanical failure (cracks etc). Understanding these forces and designing the stator windings with suitable stiffness and strength would help avoid stator winding fatigue.

b) Shaft / Coupling: The large currents involved with re-synchronising back into the grid produce electromagnetic torque that are capable of twisting the shaft or the drive train the generator is connected to. Designing the drive train with correct distribution of mass ensures a robust shaft / coupling arrangement.

c) Rotor windings: The current surges that flow through the stator windings induce voltages in the rotor windings. If the rotor windings are not provided with sufficient insulation, some of these voltage spikes are capable of breaking down the rotor insulation and thereby damaging the rotor.

d) Rotor rectifier assembly: The rotor rectifier assembly is responsible for providing the DC current to the rotor field winding. The voltage transients that could damage the rotor winding insulation could also damage the rectifier assembly. To avoid this, additional protection needs to be provided to the rectifier.

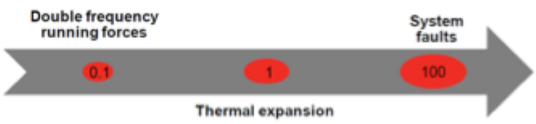


Figure 10: Relative magnitudes of forces on stator windings

2.3.2 Complex gearbox

A variable speed transmission is necessary to decouple the turbine rotor speed from the speed of the generator that is fixed to the grid. A hydrodynamic gearbox is one of the mechanisms used for wind turbines [4].
The hydrodynamic gearbox combines a gear unit with a hydrodynamic torque converter. The torque converter uses adjustable guide vanes to change the torque [5]. Variable speed transmission is generally more complicated than a conventional fixed ration gearbox.

2.3.3 Increased drive train mass

The drive train of the directly coupled synchronous generator with a variable speed transmission could be heavier than a PMG with a fully rated converter. This is because a PMG is much smaller than a wound rotor synchronous generator. In addition, a heavy variable speed transmission is added to the drive train. However, it should be noticed that a heavy transformer is necessary for a fully rated converter PMG wind turbine. On the other hand, a directly coupled synchronous generator drive train system may not need a transformer at all. However it can be argued than the transformer of the converter system can be placed at the bottom of the tower in order to reduce the mass on top of the wind turbine.

Conclusion

A directly coupled synchronous generator with a variable transmission benefits from a harmonic free, transformer free, better fault current contribution and possibly greater reliability. However the there are challenges associated with the topology, such as low voltage ride through and a complex gearbox arrangement. Nevertheless, this topology is one of the favourites for very large wind turbines.

References

[1] Wind Energy Factsheets - 2010, By the European Wind Energy Association

[2] The Cornelis A. Plet, M. Graovac, Timothy C. Green, and R. Iravani, "Fault Response of Grid-Connected Inverter Dominated Networks", pages 1-8, IEEE Power and Energy Society General Meeting, 2010.

[3] E. Muljadi, V. Gevorgian, N. Samaan, J. Li, and S. Pasupulati, "Short Circuit Current Contribution for Different Wind Turbine Generator Types", IEEE Power and Energy Society 2010 General Meeting, Minneapolis, Minnesota, July 25–29, 2010

[4] Andreas Basteck, "WinDrive - Large Wind Turbines without Frequency Converter", Voith Turbo Wind GmbH.

[5] H. Müller, M. Pöller, A. Basteck, M. Tilscher, and J. Pfister, "Grid Compatibility of Variable Speed Wind Turbines with Directly Coupled Synchronous Generator and Hydro-Dynamically Controlled Gearbox", Sixth International workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, 26–28 October 2006, Delft, NL.

Cummins Generator Technologies Ltd
Barnack Road, Stamford
Lincolnshire, PE9 2NB, UK

Tel: +44 (0) 1780 484000
Fax: +44 (0) 1780 484100
email: info@cumminsgeneratortechnologies.com

www.cumminsgeneratortechnologies.com

WP_WIND_S_EN_GS_01